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SUA SODA ASH PROJECT

Phase III Investigations

Memorandum No.15

BRINE WELLFIELD DESIGN

December 1984
7696/PG

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1. SYNOPSIS

An initial wellfield design is developed on the basis of resource parameters defined in Memorandum No.14, dated December 1984, to meet the anticipated process demand of 18 x 10^6 m^3 of brine per annum at specific gravities in excess of 1.10.

The long term performance of the wellfield is examined and it is concluded that an ongoing programme of well replacement will be necessary based on careful monitoring of the production wells, aquifer and aquitard piezometric surfaces in the wellfield area and variations in brine quality with depth.

The process of brine dilution by recharge is examined and it is deemed prudent to allow for a progressive 50 percent increase in wellfield area between years 5 and 10 of operation of the scheme in order to ensure long term availability of brine with adequate concentrations of dissolved salts.

Recommendations are given as to well design and pumping equipment to form a basis for cost estimates and operation and maintenance procedures are discussed.

A wellfield monitoring system is proposed and it is recommended that a resource management model should be established to facilitate planning of the well replacement programme and exploration of potential areas for wellfield expansion in the long term.

It is concluded that with a flexible approach to wellfield development and careful attention to management based on the recommended monitoring procedures, the resource as defined in Memorandum No.14 will sustain the anticipated process demand for a period in excess of 25 years.

2. OBJECTIVES

In Memorandum No.14, dated December 1984, the brine resource is defined on the basis of the investigations undertaken by WLPU from July 1982 to date and resource parameters are established for wellfield design. In addition, the process of long term brine dilution as a result of recharge to the resource is examined to permit the assessment of this effect for design purposes.

In this Memorandum the design of a production wellfield is developed both to establish the viability of supplying the process demand over a period in excess of 25 years and to form a basis for the preparation of cost estimates by Seltrust Engineering Limited (SEL).

3. DESIGN PARAMETERS

The brine demand and resource parameters for use in design of the wellfield are set out below.

3.1 Brine Demand

The assumed brine demand corresponds to the latest figures supplied by SEL on the basis of process considerations as follows:

Annual brine demand for production
of 300 000 t/y of soda ash: 18×10^6 m^3

Normal demand from the wellfield
(pumped over 10 months each year): 660 l/s

Maximum demand: 1 000 l/s

The feasibility of meeting a peak demand of 1 200 l/s is also to be examined.

3.2 Brine Quality

On the basis of discussions with SEL it is assumed that the minimum acceptable specific gravity for brine supplied to the solar ponds is 1.100. It is assumed that the process of dilution arising through recharge by rainwater will not alter the relative concentrations of the marketable products held in solution.

3.3 Resource Parameters

The resource parameters adopted for design are carried forward from Memorandum No.14 as follows:

Depth of laminated aquifer/aquitard sequence: 30m

Defined area of exploitable resource: 1 000 km^2

Average total thickness of aquifer horizons: 10m

Average total thickness of aquitard horizons: 20m

Aquifer transmissivity: Typically in the range 150 to 400m^2/d

Aquifer storage coefficient: 0.0005

Aquitard specific yield: 0.05

Aquitard vertical permeability: 0.002 m/d

Brine quality: Average specific gravity 1.12

4. AREAL EXTENT OF THE WELLFIELD

From the computer modelling undertaken as part of the Phase II investigations it was concluded that a wellfield area of approximately 200 km^2 would be required to sustain a design yield of 950 l/s.

This finding was based on modelling which assumed zero recharge and the well spacing was governed principally by the need to limit well interference effects in the short term. Subsequently it has been established that the long term performance of the wellfield will depend predominantly on the effect of recharge by direct precipitation and the design yield of the wellfield has been reduced to 660 l/s, or 18 x 10^6 m^3 per annum pumped over 10 months.

Since the computer model has demonstrated that drawdowns will be limited essentially to the area of the wellfield, it follows that the wellfield area must be adequate to receive recharge comfortably in excess of abstraction from the aquifer.

Mean annual rainfall at Sua Pan is approximately 400mm and hence the total direct precipitation falling on an area of 200 km^2 will be some 80 x 10^6 m^3 in an average year which is more than four times the proposed annual abstraction.

Hence a wellfield area of 200 km^2 is deemed appropriate as a basis for design trials allowing for the fact that evaporation losses will be sustained before the recharge infiltrates below the capillary zone and acknowledging that the wellfield must operate through drought sequences, when rainfall may be below average for a number of years.

5. COMPUTER MODELLING

The computer model set up to simulate hydraulic performance of the brine wellfield is described in Memorandum No.1 dated February 1984, which outlines the finite difference approach upon which the model is based, the simplifying assumptions which have been made and the limitations with regard to application of the results.

A further simulation designed specifically to investigate the effects of recharge is described in Memorandum No.11, dated September 1984.

With the benefit of the improved definition of resource parameters arising from the Phase III investigations, further computer modelling has now been undertaken, as described below.

5.1 Hydraulic Model

The basis of the model remains essentially as described in Memorandum No.1. The superficial investigations undertaken to the south of the Sua Spit and on the Ntwetwe Pan are not deemed to provide an adequate basis for revision of the assumed boundary conditions, particularly since drawdowns have been shown to be confined essentially to the wellfield area, so that remote boundaries have little effect.

The finite difference mesh remains unchanged from the earlier work, as shown on Fig.1.

The site investigations undertaken during Phase III have led to the following revisions to the aquifer/aquitard parameters input to the model:

a) Velocity profiling has confirmed a total aquifer thickness of about 10m but has indicated significant aquifer horizons at shallow depths (less than 10m in some cases). To investigate the effects of shallow aquifers overlain by reduced aquitard thicknesses two aquitard/aquifer configurations have been examined; firstly, a 10m aquifer overlain by a 20m aquitard, as considered in the earlier work, and secondly, a sequence comprising a 10m aquifer overlain by only 10m of aquitard.

It is emphasised that the model can only cope with a single aquifer overlain by a single aquitard. This constitutes an idealised representation of conditions known to exist in the field where a number of discrete aquifer horizons at various depths make up a combined average thickness of about 10m.

b) The additional transmissivity data obtained from the Phase III maxiwells has led to a revision of the assumed transmissivity contours, as shown on Fig.2. On the basis of the updated transmissivity contours, the wellfield area was adjusted as shown on Fig.1 from that adopted during the earlier modelling.

5.1.1 Drought Simulation

It has already been established that, in an average rainfall year, recharge to a 200 km^2 wellfield as a result of direct precipitation will exceed abstraction and the brine table, drawn down due to dry season pumping, will in general recover fully following recharge during the rainy season. This average regional picture will be subject to variations locally, for example where a near surface aquiclude prevents recharge from reaching the aquifer. It is also necessary to examine the behaviour of the system under drought conditions and the computer model has been used to study a design drought sequence based on rainfall records from Francistown for the period 1922 to 1983, as plotted on Fig.3. The average annual rainfall over this period was 462mm and a minimum of 116mm was recorded in 1965, preceded by 251mm in 1964. On the basis of these figures, a drought sequence was selected for a computer simulation extending over 36 months.

In month 0, the brine table was assumed to lie 1m below the Pan surface. Continuous pumping at 660 l/s was assumed over the simulation period with individual well pumping rates proportional to aquifer transmissivities so as to give equal drawdowns at all wells in the absence of storage depletion and interference effects.

Recharge over the 36 month period was assumed to occur as follows:

Year 1: Total recharge of 200mm, input as 50mm per month over months 9 to 12 inclusive.

Year 2: Total recharge of 100mm, input as 25mm per month over months 21 to 24 inclusive.

Year 3: Total recharge of 300mm, input as 75mm per month over months 33 to 36 inclusive.

The results of the simulation are presented on Figs 4 and 5 for the 10m and 20m aquitard cases respectively in the form of aquifer drawdown contours at a radius of 650m from the well positions at the end of month 32. The variations in drawdown in the aquifer and aquitard over the drought sequence are plotted on Figs.6 and 7.

Well drawdowns (excluding losses) are obtained by adding 6.7m to the values plotted on Figs.4 and 5.

A maximum drawdown of 4.4m is indicated for the 20m aquitard case at Node 105, in the centre of the wellfield at the end of month 32, corresponding to a well drawdown of 11.1m.

In practical terms this means that any aquifer horizons occurring at a depth less than 12.1m below the Pan surface in the area of Node 105 would become unconfined.

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Although the computer model cannot simulate local aquifer dewatering, it is known that over much of the exploration area the main aquifer horizons lie deeper than 12.1m and hence any fall off in well yields arising through aquifer dewatering in the centre of the wellfield could be offset in practice by increased pumping from wells in high transmissivity areas near the perimeter.

It is concluded that a continuous brine supply of 660 l/s could be maintained through the design drought sequence, subject to judicious redistribution of well pumping so as to limit drawdowns in the centre of the wellfield.

5.1.2 Drawdowns and Extraction Rates

The computer simulation is based on a total of 52 wells with mean abstraction equivalent to 3.25 $l/s/km^2$ of wellfield area.

The extraction rates assumed in the simulation for each well are tabulated overleaf:

Node No.	Pumping Rate l/s	Node No.	Pumping Rate l/s
55	9.5	123	13.9
56	11.7	124	12.5
57	13.5	135	11.6
58	12.2	136	13.5
59	8.7	137	14.6
71	12.5	138	14.7
72	15.0	139	13.3
73	17.2	140	11.8
74	15.3	151	11.2
75	11.5	152	12.6
87	13.1	153	13.3
88	15.2	154	13.1
89	16.7	155	12.0
90	15.5	156	10.9
91	13.4	167	11.0
92	11.0	168	11.8
103	12.5	169	12.0
104	15.1	170	11.5
105	16.1	171	10.6
106	15.8	172	9.9
107	14.2	183	10.0
108	12.2	184	10.7
119	12.2	185	10.5
120	14.4	186	9.8
121	15.4	187	9.2
122	15.4	188	8.7

These figures correspond to a total wellfield yield of 660 l/s. A maximum well pumping rate of 17.2 l/s is indicated for a well in Node 73.

Well drawdown contours for the end of the dry season following an average rainfall year are plotted on Figs.8 and 9 for the 10m and 20m aquitard cases respectively. Drawdowns are greater for the latter case because the vertical hydraulic gradient is lower, resulting in reduced leakage into the aquifer.

A maximum drawdown of 10.5m at the well is indicated for the 20m aquitard case in the centre of the wellfield reducing to 7.6m at the perimeter. Allowing for well losses, the corresponding total drawdowns would be approximately 12.1m and 9.2m respectively.

The computer simulation has also been run for a total pumping rate of 1 000 l/s and the results suggest that the proposed wellfield could deliver this flow for more than 6 months. After 6 months of pumping at 1 000 l/s estimated average well drawdowns lie in the range 15.9m (wellfield centre) to 13.6m (perimeter) inclusive of well losses for the 20m aquitard case.

It is emphasized that, in practice, permissible pumping rates will be determined on the basis of tests carried out after installation of each well so as to limit drawdowns to acceptable levels in the short term. Based on continuous monitoring of wellfield performance, pumping rates at individual wells will be adjusted from time to time with some wells being taken out of service completely to be replaced by increased pumping at other existing sites or by replacement wells. Nevertheless, the pumping rates and drawdowns indicated by the computer simulation are considered to provide a suitable basis for the initial wellfield design.

5.2 Brine Quality

Having established in quantitative terms that the proposed wellfield will sustain the process demand in the long term, it is necessary to determine whether or not a brine of acceptable quality can be delivered to the solar ponds for a period sufficient to ensure viability.

In Memorandum No.11, dated September 1984, it was suggested on the basis of a preliminary computer simulation that the quality of brine entering an aquifer at 20m depth would begin to decline after about 25 years.

In Memorandum No.14, dated December 1984, the question of brine quality in the long term is addressed in more general terms and two alternative methods are proposed for use in design. These are applied below to the two simplified aquifer/aquitard configurations which have been examined in the recent computer modelling.

5.2.1 Upper and Lower Bound Method

The following upper and lower bound cases are postulated for the downward progress of the recharge/in-situ brine interface through an aquitard overlying an aquifer supplying brine to the pumped wells:

Upper Bound - Complete Mixing

The recharge process is conceived as having maximum effect on the specific gravity of the brine entering the aquifer at depth if the recharge entering the overlying aquitard at S.G. 1.0 is immediately and intimately mixed with all of the brine stored in the aquitard pore space, causing a slow but continuous decline in specific gravity at any abstraction well fed by the aquifer.

The aquitard phreatic surface will be drawn down very steeply in the immediate vicinity of each well but for practical purposes it may be regarded as a horizontal plane moving vertically in response to vertical leakage into the underlying aquifer and to recharge from above.

Based on laboratory testing, the average porosity of the sediments occurring at less than 30m depth is indicated to be 0.60. Downward flow through the aquitard is conservatively assumed to take place through an effective pore space of 30 percent of the aquitard volume.

Hence, if the brine pumped from the wellfield is assumed to be derived solely from aquitard storage, the average vertical velocity in the upper aquitard over the wellfield area of 200 km^2 may be calculated. For an abstraction rate of 18×10^6 m^3/y an average vertical velocity of 0.3m/y is indicated.

Assuming that recharge enters the aquitard at S.G. 1.0 and passes into the underlying aquifer at the specific gravity which results from instantaneous, complete and intimate mixing with the stored brine, a stepwise calculation may be carried out to yield the variation with time in the S.G. of brine passing into the aquifer.

The results are plotted as the upper bound curves on Figs.10 and 11 corresponding to 10m and 20m aquitard thickness respectively. An initial stored brine specific gravity of 1.12 is assumed and the curves shown brine entering the aquifer at S.G. 1.10 after 6 years for the 10m aquitard and after 24 years for an aquitard thickness of 20m.

Lower Bound - No Mixing

The recharge process is conceived as having minimum effect on the specific gravity of the brine entering the aquifer at depth if the recharge simply displaces the underlying brine stored in the aquitard with no mixing at the interface. Under these conditions the brine pumped from an abstraction well will maintain full strength for a period dependent upon the aquitard thickness, before declining instantaneously to 1.0.

In this case the calculation is trivial and leads to the findings that the interface will reach the aquifer after 33 years for a 10m aquitard and after 67 years for an aquitard thickness of 20m.

The results are plotted for comparative purposes as the lower bound curves on Figs.10 and 11.

5.2.2 Analytical Method

In Memorandum No.14 an analytical solution to the problem of solute dispersion in a one dimensional uniform flow field is presented, in the form of an equation derived by Ogata and Banks (1961).

The equation is written in a form directly applicable to uniform vertical flow through the aquitard with recharge entering continuously at S.G. 1.0 at the upper boundary.

The equation may be applied to determine the specific gravity of the brine in storage at any depth y below the top of the aquitard after any time, t.

Solutions have been obtained for assumed diffusion coefficients of 0.005 and 0.01 for the 10m and 20m aquitard cases and the results are plotted on Figs. 10 and 11 for comparison with the upper and lower bound approach.

For a 10m aquitard thickness the analysis indicates brine entering the aquifer at S.G. 1.10 after 5.5 to 8.5 years and for a 20m aquitard after 17 to 25 years.

5.2.3 Interpretation of Results

The results plotted on Figs.10 and 11 are all based on the assumption of homogeneous isotropic conditions. The conditions at Sua Pan are neither homogeneous nor isotropic. The aquifer and aquitard horizons are horizontally laminated and the recharge is of lower density than the in-situ brine. Horizontal aquicludes are known to exist in the form of calcrete and chalcedony layers and no evidence has been obtained from the fieldwork of vertical discontinuities in the sequence which might constitute preferential recharge flow paths. Each of these factors will tend to retard the dispersion process and hence the plotted results are judged to be conservative in terms of the periods indicated before dilute brine enters an aquifer at depth.

Furthermore, no account has been taken of the brine stored initially in the aquifer horizons. At all times the brine reaching the well will comprise contributions from both aquifer and aquitard storage with the aquifer contributions declining with time. The effect of aquifer storage will serve to prolong substantially the period over which full strength brine is available from the well.

Taking account of the occurrence of high yielding aquifer horizons at less than 10m depth in some areas, brine S.G. may decline to 1.10 after less than 5 years of pumping in certain wells whereas in others, where the predominant inflows occur at 25 to 30m depth, high yields of full strength brine may be anticipated for 25 years or more.

At sites where high transmissivities are recorded but an early decline in brine quality occurs, a replacement well may be installed with blank casing set to a depth sufficient to cut off flows from near surface aquifers with only the deeper horizons screened. This procedure could extend the viable life of an abstraction site by 20 years or more under favourable conditions.

Taking all of the above factors into consideration it is considered probable that the initial wellfield area, with proper management and appropriate relocation and rescreening of wells, will sustain a yield of 18 x 10^6 m^3 per annum of brine at a specific gravity greater than 1.1 for up to 25 years.

However, the anticipated variation in conditions over the area is such that extension of the wellfield beyond the initial area may be required to maintain acceptable brine quality. Careful monitoring of the initial wellfield will enable any necessary extensions to be planned in advance and low cost well construction techniques are favoured so that the cost implications of a significant extension of the initial wellfield will be minor relative to the total capital cost of the project.

The extent and timing of wellfield extensions, if required in the light of performance monitoring, cannot be predicted with confidence at this stage, but it is considered prudent to adopt a conservative approach in terms of the project cash flow by assuming a phased 50 percent extension in the area covered by the wellfield, with replacement wells sited on a 2km grid, over the period 5 to 10 years after the commencement of full scale abstraction.

6. WELLFIELD LAYOUT

6.1 Initial Layout

The results of the computer modelling have demonstrated that a wellfield 200 km^2 in area, sited as shown on Fig.1 and comprising 52 production wells, is capable of meeting the process demand in the long term with acceptable drawdowns under both average and peak flows.

A notional wellfield layout corresponding closely to the configuration assumed in the modelling is shown on Fig.12.

The 52 wells are set out on a 2 km square grid and feed a main delivery line to the solar ponds area. In practice two or more main delivery lines might be used and the notional pipework configuration shown is subject to optimisation on the basis of detailed hydraulic analysis.

The layout shown is deemed appropriate for the initial development of the wellfield but the pattern of abstraction is likely to change progressively on the basis of performance monitoring during the early years of operation.

Since the layout is based on transmissivity contours extrapolated beyond the area explored to date, it is recommended that three further simple transmissivity exploration wells, sited as shown on Fig.13, should be drilled and test pumped prior to finalisation of the detailed design. Since the transmissivity contours are conservative in assuming a roughly linear decline from know values at the exploration well sites to zero at the assumed boundaries, it is considered likely that these wells will indicate conditions at least as favourable as those assumed in the modelling.

In addition to confirming assumed transmissivity data, the proposed wells could be used for rig proving trials and the final testing of alternative screen types which had to be deleted from the planned Phase III exploration programme.

6.2 Layout for Increased Demand

The initial wellfield layout is based on meeting a demand of 18 x 10^6 m^3 of brine per annum pumped at an average rate of 660 l/s, peaking at 1 000 l/s for short periods.

In order to meet higher demands it is likely that a larger wellfield would be required.

To supply 18 x 10^6 m^3 per annum with the pumping rate peaking at 1 200 l/s for up to 6 months it would be appropriate at this stage to allow for a 20 percent increase in wellfield area over the 200 km^2 proposed for the initial layout.

7. WELL DESIGN

The well design philosophy is influenced by the need for flexibility in adjustment of the well layout based on performance monitoring of the initial wellfield under sustained pumping.

Experience gained in the Phase III field investigations has confirmed that sand packing will be required to support the annulus between the screen and the hole wall. From consideration of entrance velocities, well losses and the need to provide an open annulus large enough for installation of the pack, the combination a 375mm diameter hole equipped with a 250mm nominal diameter screen is considered appropriate for production well design.

A wide range of water well screen types is open to consideration ranging from the efficient but very expensive Johnson wedge wire wound type to simple slotted PVC types as manufactured by Boode of Holland, Preussag of Germany and others.

The expectation that average effective well life will be short because of the need to adjust cased depths or open up new areas for pumping in the early years of operation favours the use of a low cost screen which can be abandoned in redundant wells without significant financial loss. It is not considered feasible to contemplate recovery of screens from redundant wells.

The experience gained with the various screen configurations tested on site from late 1982 to date is outlined below.

During Phase I the test wells incorporated Johnson wedge wire wound well screens. The screens had 0.3mm slots giving an open area of approximately 10 percent and were packed with a clean sand whose grading is given on Fig.14. Well W1 incorporated 200mm diameter screens in AISI 304 stainless steel. The performance of this well has proved entirely satisfactory over some 2 years of intermittent pumping at up to 27.5 l/s.

Further testing of other purpose built screens from Boode (Holland) and Preussag (Germany) was carried out as part of the twinwell programme in Phase II together with a series of twelve miniwells which employed a simple bored PVC screen with an open annulus. The performance of the twinwells was disappointing, with drawdowns larger than at the miniwells being recorded at modest flows. Very high well losses were caused by vertical flow through the filter pack in the annulus. The vertical flow originated from major brine aquifer horizons which were located at shallow depths where the holes were continuously cased. The simple miniwell arrangements proved satisfactory in those wells which remained open. High yields were being recorded with minimal losses. The problems of high head losses from the commercially screened twinwells meant that it was not possible to comment on the relative efficiencies of the different screens but the PVC screens were deemed likely to give satisfactory performance if correctly set against the aquifer horizons.

Towards the end of Phase II investigations two trial maxiwells were drilled which incorporated a low cost PVC bored screen made on site and wrapped in steel mosquito netting. This configuration was based on the successful performance of the 150mm screens used in the miniwells. Initially the wells were unpacked and gave high yields of up to 25 l/s with very low well losses. Inflow of fines through the screens did not prove a serious problem. Uncertainties with regard to long term stability of the well resulted in a gravel pack being introduced. The pack reduced the specific capacity of the well by over 50 percent, but this was again attributed in part to incorrect setting of the screens relative to the inflow horizons.

Geophysical logging confirmed the existence of several interspersed aquifer horizons throughout the upper 30m, but could not accurately define the individual aquifer layers. As a result it was decided to try continuous screening to eliminate any well losses caused by vertical flow through the packing.

During the Phase III investigations, further maxiwells were programmed to evaluate alternative well designs, all employing low cost options. In the event, the programme was curtailed and the well design trials were not completed. However, valuable information on well design was obtained from maxiwells numbered MX12 to MX16.

Maxiwells MX14, MX15 and MX16 incorporated a 250mm diameter Class 4 Duroflo pipe drilled with 20mm diameter holes to give an open area of approximately 10 percent. Various mesh wrappings were tried utilising both aluminium and polypropylene mosquito netting and a plastic geofabric wrap. The netting, with a 1mm square open grid pattern, was used to prevent excessive ingress of the gravel pack and fines. The geofabric, Netlon Type CE7/1, with its larger 5mm holes on a diagonal grid pattern was used as an intermediate internal collector to distribute the brine evenly to all the holes in the screen. Three filter pack gradings were tried, as shown on Fig.14, and step drawdown tests were used to evaluate relative well losses.

The cheaper polypropylene mosquito netting was found to have insufficient strength to span the 20mm holes in the screens and resulting bursts caused ingress of the filter pack. The aluminium netting (manufactured in Australia) exhibited adequate strength, but there are doubts about long term performance of aluminium in the brine.

Results from the test work have indicated that the well losses at the recent maxiwells are greater than those recorded for the Johnson screens at W1, but that variation in well losses between the different screening arrangements of the maxiwells is relatively small, in the range 0.01 - 0.03 Q^2. The greater well losses, measured in MX13 and MX14 were influenced by collapse of an open annulus and the subsequent use of a twin screen comprising drilled PVC pipe with an inner Johnson screen. There was no direct evidence to suggest that the geofabric distributor wrapping improves well efficiency,but further work is required in this area.

7.1 Sand Pack Grading

Where maxiwells have been successfully sand packed, as at MX16, the ingress of fines from the aquifer has not proved to be a serious problem. Two of the sand packs used (gradings A and C) are coarser than theoretically required on the basis of gradings of the aquifer materials. The findings confirm that the primary aim of the pack should be to support the walls of the hole under the inward hydraulic gradients induced by pumping rather than to filter out fine particles which might otherwise enter the well. The coarser the sand pack used the greater will be the porosity and hence the lower the well losses which are proportional to the square of the velocity through the pore space.

The coarse sand pack grading, Type C, is deemed appropriate for the production wells. The need to place the pack without "hanging up" in the annulus imposes an effective upper bound on the pack grading and the Type C grading is judged to be a suitable compromise between ease of pack installation and minimum losses.

7.2 Screen Design

On the grounds that an ongoing supply of well screens will be required through the life of the project, screen selection has been concentrated on those types readily available on the South African market. Imported screens are subject to very heavy duty and hence there is a significant economic advantage in using locally manufactured materials.

Johnson well screens would offer minimum well losses (estimated at 0.005 Q^2 from Phase I testing) but the indicated supply cost for large quantities in late 1984 is R375/m.

The estimated total cost of the maxiwell screens made up on site in 1984 was R54/m without an intermediate Netlon distributor wrap or R60/m inclusive.

Hence, for an initial wellfield comprising 52 wells each with a screened length of 24.5m the total cost of Johnson screens would be R478 000 and for maxiwell type screens R76 500 with Netlon mesh included.

A further Netlon product has been investigated for possible use as well screen. This is drainage pipe made up of welded polypropylene filaments forming a coarse mesh with up to 80 percent open area. Unfortunately this product is manufactured only in diameters up to 150mm in South Africa and larger diameters would need to be imported from Japan. A 30m sample of 250mm pipe has been obtained and is held in the WLPU Rivonia Office. However, it arrived too late for testing during the Phase III investigations. Potentially it offers the basis for a cheap and efficient well screen. However, its form of construction gives rise to reservations concerning structural strength and rigidity and it cannot be recommended without on-site trials. A cost of about R22/m is indicated for a Netlon pipe screen wrapped in steel insect mesh.

It is concluded that simple mesh wrapped well screens based on PVC or polypropylene pipes available on the South African market will be adequate for the envisaged duty at Sua Pan and offer significant economies in terms of capital cost over the more efficient Johnson screens.

It is recommended that mesh wrapped PVC screens are used during the initial wellfield development. If, as a result of wellfield performance monitoring and adjustment of well locations and pumping rates, a stable wellfield configuration is achieved with an indicated productive life of many years without local depletion, it may prove economically attractive to replace the initial wells with long term installations incorporating Johnson screens. The additional long term pumping costs arising from higher well losses in the wrapped PVC screened wells would need to be calculated and set against the capital cost of the well replacement programme.

To summarise, simple PVC screens are evidently appropriate in the short term when significant quantities of screen are likely to be lost in redundant wells, but in the longer term the more efficient Johnson screens may prove attractive on the grounds of reduced energy consumption.

Based on the foregoing considerations it is recommended that the following three simple well screen options should be tested prior to the ordering of materials for development of the initial production wellfield:

1) <u>Duroflo Pipe, slotted and mesh wrapped</u>
   250mm diameter Class 4 "Duroflo" (manufactured by Durapenta) or similar pipe with 2mm wide sawn slots to give 10 percent minimum open area and wrapped in stainless steel mesh with 1mm square openings.

   Slots are considered preferable to bored holes to give maximum support to the wrapping. Stainless steel mesh is specified in preference to aluminium because of doubts concerning long term performance of the latter material in the Sua brine.

2) <u>Duroflo Pipe, slotted and wrapped in Netlon Geofabric and mesh</u>
   Similar to (1) above, but with a Netlon Type CE7/1 inner wrapping.

3) <u>Netlon Pipe, mesh wrapped</u>
   250mm diameter Netlon continuously woven drainage pipe with 20 percent minimum open area and wrapped in stainless steel mesh with 1mm square openings.

Until final pumping trials can be undertaken on site, preliminary design should proceed on the basis of option (2) above which is the most expensive of the three options and is considered most likely to be finally adopted.

To minimise the length of time over which the hole has to stand open before the screen is installed, and hence limit the risk of collapse, a quick and efficient jointing system is required for the screens, which will be supplied in 6m lengths. A system based on simple bolted steel hangers is favoured.

Details of the preferred screening alternative and recommended jointing system are shown on Fig.15.

7.3 Screen Setting

An indication of the locations of the aquifer horizons will be obtained from the cuttings logs during well drilling. It will not, however, be possible to set screens with confidence by reference to these logs and it is recommended that all wells should be drilled to 32m and continuously screened from 5 to 29.5m depth to ensure that all major inflow horizons are screened below 5m depth.

The top 5m of the hole should be cased so as to limit cascading flow from near surface aquifer layers and from recent recharge of low specific gravity.

If the specific gravity of brine pumped from a high yielding well is found to decline due to low S.G. inflows at shallow depth, a replacement well can be drilled alongside, cased to a greater depth so as to cut off the shallow inflows whilst permitting continued abstraction from deeper high yielding aquifers.

To determine the best depth at which to set the casing in the new well, an uphole velocity profile should be run from 5 to 30m depth on the original hole.

From 29.5 to 32.0m depth a blank cased section should be provided to form a chamber in which to locate the pump intake set at 30m depth without causing damage to the sand by local turbulence and also to form a sump for storage of any coarse particles which settle out after being drawn in through the screen.

Details of the screen and pump intake setting are shown on Fig.16.

The deep pump setting will allow high drawdowns to be achieved in wells with deep aquifer horizons.

7.4 Well Construction

The wells will be drilled by the hydraulic rotary method using reverse circulation with the in-situ brine as the drilling fluid. Revertible organic polymer type drilling muds may be required for drilling through exceptionally loose formations.

A draft performance specification for the proposed drilling and well construction equipment is presented in Appendix A to which reference should be made for further details of the techniques to be adopted.

7.5 Pumping Equipment

The pumping equipment at each well must be capable of delivering up to 25 l/s of brine at S.G. 1.15 against a total head of up to 50m.

Two principal types of installation have been considered:

1) Submersible pumps with a centrifugal impellor unit and direct coupled motor suspended down the hole.

2) Displacement type or centrifugal pumps with the impellor unit driven by rods from a surface power source.

Submersible pumps are in general cheaper than surface driven units and their installation is easier and more flexible. However,they are more prone to blockage by silt and this has proved to be a serious problem in the limited trials undertaken with this type of pump in test wells.

Major manufacturers of submersible electric pumps which would meet the head and flow requirements include Grundfos Ltd, Sigmund Pulsometer Ltd and the Johnston Pump Company.

Simplicity, rugged reliability and an ability to pump silt are of fundamental importance in the pumping of brine from low cost wells at Sua Pan and these requirements favour the use of surface driven units. Major manufacturers include Mono Pumps Ltd, Ingersoll Rand, Sigmund Pulsometer Pumps Ltd and the Johnston Pump Co. Ltd.

The most widely used surface driven pumps in Southern Africa for duties comparable with those anticipated are manufactured by Mono Pumps Ltd and Mono pumps have been used successfully in all wellfield pump testing undertaken to date.

They operate on a simple positive displacement principle with a helical chromed steel rotor running in a deformable rubber stator giving a high tolerance to suspended solids.

At W1 a Mono BH400 unit has been installed for more than 2 years and has operated over long periods without significant corrosion or reliability problems.

In general the pump units themselves have proved reliable and easy to use during the tests at other wells, but several problems have occurred with the diesel engines used to drive the pumps. It is envisaged that electric motors will be used for the production wells, which will prove less troublesome and require less maintenance than diesel engines.

Several points arose during the testing which should be discussed with the pump manufacturer:

a) The belts connecting the engines to the pump head had a tendency to fall off the drive pulleys, partly due to the difference in night and day temperatures causing expansion of the belts. For the production wells a system for automatic tensioning of the belts is suggested and the belts should be well protected from the harsh environment of the Pan.

b) The gland packing seals at the pump head were susceptible to erosion by the silt in the brine being pumped from the well. This will be a problem especially during the initial phases of well development, when the silt load will be greatest. The gland packing should be capable of resisting this erosion, and the pump shaft should be fitted with a thrower ring to prevent any leakage from reaching the pump bearings. We understand that more recent Mono BH series pumps have an improved P.T.F.E. gland packing and a thrower ring fitted as standard.

c) The electric motors must be capable of resisting the adverse effects of the sandstorms occurring on the Pan. It is recommended that the well head be enclosed in a weatherproof enclosure, with adequate ventilation provided for cooling. Ventilation should consist of sand trap type louvres positioned to avoid sand access around the pump shaft and motor fan cowling.

Experience to date with pump testing on the Pan has demonstrated that Mono type borehole pumps are well suited for use on the production wells and the BH400 unit meets the design head and flow requirements. It is recommended that design should be carried forward on the basis that Mono BH400 pumps will be used. However, it is suggested that competitive tenders for pumping equipment should be invited before a final decision is made to ensure keen pricing and to permit a review of the available options.

As the drive shaft passes centrally through the riser column in the Mono design, considerable head losses occur between the intake position and the pump head. For a 30m riser (10 No. 3m lengths) the design head loss for a pumping rate of 10 l/s would be 3.6m. The losses in the riser increase with the square of the pumping rate.

The electric motors will need to be set above the maximum anticipated flood level at each well location. A topographical survey of the wellfield area will be required to enable the design flood levels to be established.

8. OPERATION AND MAINTENANCE

After drilling, screening and development of the well the pumping equipment should be installed and coupled to the first 200m of delivery pipework. An open joint should be left at 200m from the well to permit the initial flow of silt laden brine to be discharged to waste on the Pan. Pre-production testing will comprise stepped drawdown, constant rate and recovery tests and the results will be used to establish the production pumping rate. The required tests are as described in Memorandum No.5 dated May 1984 for exploration wells.

After testing, the delivery line may be connected up and the well brought on stream. It will require daily inspection for the first week of pumping to confirm that the selected pumping rate is appropriate and to make good any initial leaks in the pipework and faults in the equipment.

Thereafter, each well should be visited at least once a week. The frequency of these visits will be dependent on the sophistication of the remote monitoring system. It is assumed at present that the monitoring system will include a remote indication of the load on the pump motor, which will give warning of the pump sticking or drive belt failure.

The major items of maintenance will be as follows:

a) Electric Motor:
This will require maintenance as detailed by the manufacturer, including checking of the brushes and lubrication of the bearings at regular intervals. A check should also be made on the amount of sand collecting in the fan housing, as an excessive build-up could cause the motor to trip.

b) Drive Belts:
These will require careful inspection to check for wear and slackness. A good supply of replacement belts should be kept on site.

c) Pump:
The drive head will require regular greasing of the top bearing, and a regular check on the gland packing seal on the shaft. Sand may well collect in the housing around the bearing and this must be cleared away from the gland seal to prevent wearing of the seal or shaft.

d) Well Screen:

Soon after the commencement of long term pumping a check should be made on the level of the gravel pack, which may well settle due to consolidation. The gravel should be topped up periodically to Pan surface level. The position of the screen should also be checked to ensure that no settlement has taken place.

e) Pipework and Fittings:

Regular checks should be made for any pipework leaks or signs of corrosion and remedial work then carried out as necessary. All valves should be opened and closed at least weekly to prevent seizure. Other fittings such as flow meters will require maintenance as detailed by the manufacturers.

During the envisaged two month shutdown each rainy season a systematic maintenance programme should be carried out to ensure that all production wells necessary to sustain the required yield are in good operating order. This may entail lifting of rotor/stator units for inspection and replacement if necessary and the pumping out of accumulated sand from the sump, depending on operating experience.

9. PROCEDURES FOR WELL FAILURE OR EXHAUSTION

Throughout the life of the Project, new wells will need to be installed and developed as required in order to ensure that brine is continuously supplied to the process plant in the required quantities. The necessity for new wells will arise from a number of potential causes and it is tentatively envisaged that perhaps 5 to 10 wells will require replacement for one reason or another each year.

It is probable that certain wells sited in areas of the Pan underlain by low permeability soils will become depleted prematurely and relocation will be required to maintain full production. Wells near the centre of the wellfield will be liable to early depletion due to the interference effects from the surrounding wells and in some areas screens may become clogged due to excessive migration of fines.

Monitoring of the wellfield will give an early indication of the impending depletion of wells. New wells can then be drilled in good time to relocate the pumping equipment when necessary. The location of the new wells will depend on the monitoring results, but it is probable that infilling will be possible within the initial wellfield area before extension towards the western, northern and eastern boundaries of the resource.

Continued depletion of the initial wellfield may involve extending the spur delivery lines to the west, to pick up the areas of high transmissivity near test wells M2 and MX16.The failure of a few individual wells will not affect the process adversely, as the output from the other wells can be increased to make up the deficit in the short term. However, replacement wells will need to be drilled as quickly as possible in order to avoid excessive drawdown of the remaining wells.

The drilling and pump installation rigs should be on continuous standby for the installation and development of new wells as required and screen and gravel pack materials should be stockpiled on site at all times sufficient for at least 10 replacement wells.

10. WELLFIELD MONITORING SYSTEM

Long term monitoring of the production wellfield is necessary for two reasons:

a) To observe and record wellfield drawdown and recharge.

b) To monitor changes in the brine quality at varying depths.

Records of drawdowns are essential to check on both the performance of individual wells and on the wellfield as a whole. Excessive drawdowns would indicate imminent dewatering of aquifer horizons which would lead to reduced well output. By keeping regular records of aquifer and aquitard drawdowns, short and long term well performance trends may be predicted, and by timely replacement of failing wells, continuity of brine supplies will be assured.

Monitoring of brine quality will involve measuring specific gravity at varying depths supplemented by routine laboratory analyses on selected samples. This will ensure that advance warning is given of excessive dilution of the brine, so that alternative wells can be developed in good time.

10.1 Drawdown and Recharge Monitoring

During Phases I and II piezometers were used to monitor the piezometric surfaces in the aquifer and aquitard. In these early short duration tests a rapid response from the monitoring system was considered important and 25mm diameter Casagrande piezometers were regarded as more suitable than the larger 125mm bored PVC screen miniwells in which the effect of well storage is significant. Also, an open monitoring well records only the lowest fluid pressure and thus does not permit the measurement of pressure at more than one specific elevation in a well. The location of a piezometer tip precisely within the aquifer horizon is crucial in obtaining meaningful results from classical Theis or Jacob methods of analysis on short duration tests.

Later investigations involved long term pumping tests where variations in pore pressure in the aquifer were very slow, and so the time lag in response due to storage in a monitoring well was not important.

The resource consists of several alternating aquifer and aquitard horizons and thus it was considered preferable to use open monitoring holes rather than individual piezometers whose correct location within an aquifer layer was found to be very diffilcut.

For these reasons, the use of monitoring wells is considered adequate for the long term study of the fluctuations in aquifer piezometric levels throughout the production wellfield.

Two types of monitoring wells have been used successfully during the investigations to date:

a) A miniwell specification hole drilled to 200mm diameter and utilising a 125mm diameter bored PVC screen with mosquito netting.

b) A smaller 150mm diameter well with a 75mm diameter slotted PVC screen also with mosquito netting.

Both types of monitoring well could very easily be constructed by the drilling rig used for the production wells. The miniwell type has the advantage that it will accept a Braystoke velocity meter to determine inflow horizons. Both types of monitoring well will accept Ott continuous level recorders as used during the Phase III studies.

The Ott autographic level recorders have proved reasonably reliable under very severe conditions with little protection and provide a very useful visual record of changes in piezometric levels. Some form of protection is essential at each location where these are used. A low cost blockwork hut would provide the required level of protection.

An initial array of 19 monitoring wells is proposed as shown on Fig.12. The inner group of five wells, Type A, should be constructed to the miniwell specification and equipped with Ott recorders or similar. The outer ring, Type B, need only be drilled to 150mm diameter to allow installation of the smaller 75mm diameter screen and can be manually dipped. At each location a low cost hut should be provided for protection from the elements and to avoid accidental traffic damage. Alongside each monitoring well a shallow auger hole should be provided for brine table monitoring.

Over the first six months of wellfield operation the Ott recorders should be fitted with 7 day clockwork and charts. The recorders would be serviced weekly at the Type A monitoring wells with the Type B wells and auger holes dipped at corresponding intervals.

Subject to satisfactory performance of the wellfield after six months, the Ott recorders could be modified for a 30 day service interval with the frequency of Type B and auger hole dippings reduced correspondingly.

All monitoring wells should be drilled to 30m depth and sand packed. Auger holes should be of 150mm diameter and at least 3m in depth screened with 75mm diameter slotted PVC pipe, mesh wrapped and sand packed. Each monitoring well and its adjacent auger hole should be set in a common concrete plinth.

During the weekly inspection and maintenance visit to each well the following data should be recorded:

1) Discharge - using an in line flow meter

2) Drawdown - electrical contact dipmeter in riser column dip tube

3) Specific Gravity - hydrometer or conductivity meter

10.2 Brine Quality Monitoring

The question of long term variation in brine quality as a result of sustained abstraction from aquifers at different depths is explored in Section 5.2. The problem is complex and the only solutions available assume homogeneous isotropic conditions. Conditions in the field are known to be neither homogeneous nor isotropic and so significant deviations are anticipated from the broad picture indicated by modelling and analysis.

The monitoring of brine quality at various depths in the aquifer and aquitard sequence therefore assumes great importance, particularly as a means of predicting the arrival of dilute brine at the production wells which might necessitate replacement wells with lower screen settings close to the original sites or new wells sited elsewhere.

It is essential to obtain indications of brine quality at specific depths in addition to recording the quality of brine pumped from the wells.

This can best be achieved by using a series of Casagrande type porous pot piezometer tips set at different depths in a single hole and isolated from one another by bentonite sealing layers.

A single 375mm production well type borehole could accommodate six piezometers equipped with 25mm standpipes and set in sand at 5m nominal depth increments, as shown on Fig.17.

A total of 8 monitoring wells of this type (Type C) are proposed, located as shown on Fig.15.

After installation the tubes would be blown out using compressed air and checked for recovery. Considerable variations in recovery rate would be expected between tips set in aquifer and aquitard horizons and some tips may recover too slowly to yield samples in a reasonable time. The preferred method of testing the quality of the brine in each tube is therefore by use of a down the hole conductivity probe. Each standpipe must be clearly labelled showing the depth at which the corresponding tip is set.

Each month the tubes should be completely blown out and conductivity readings taken on the subsequent brine inflows.

11. WELLFIELD MANAGEMENT

Day-to-day wellfield management decisions will require a sound understanding of the hydraulics of the aquifer/aquitard sequence and in particular of the processes of leakage and recharge.

After initial pump testing of all production wells, it will be possible to formulate general operating rules laying down the procedures to be adopted in response to various different forms of well failure such as excessive drawdown, low brine S.G. and excessive inflow of suspended solids. These rules will provide a basis for the day-to-day operating decisions required to maintain full brine production in the short term, but long term operating strategy will require a more sophisticated approach involving computer modelling techniques.

Once the results of the initial well tests are to hand, it is recommended that a resource management model should be set up to provide long term predictions of behaviour, including early warning of the need for major revisions to the well layout or extension of the wellfield into new areas.

The data input to the model would be progressively refined on the basis of wellfield monitoring as outlined in Section 10.

It is envisaged that wellfield performance predictions would be provided in the form of a report to management every six months, taking into account any anticipated changes in the quantity or quality of brine required as feed to the solar ponds and incorporating recommendations on the pattern of well pumping for the following six month period. The report would also indicate requirements for the investigation of new resource areas should this become necessary.

The production well drilling rig could be used to good effect for exploration work when not required to service existing wells or drill replacements.

12. CONCLUSIONS

It is concluded that an initial wellfield comprising 52 wells sited on a 2 km grid and covering an area of some 200 km^2 will supply 18 x 10^6 m^3 per annum of brine pumped at an average rate of 660 l/s over 10 months each year. The proposed wellfield should sustain pumping at higher rates for short periods and pumping at 1 000 l/s is considered feasible for periods of up to 6 months if the average annual abstraction rate of 18 x 10^6 m^3 is not exceeded.

In order to increase the maximum pumping rate to 1 200 l/s for periods of up to 6 months, a 20 percent increase in wellfield area is likely to be required assuming no increase in total annual demand.

To maintain the design delivery rate in the long term, replacement wells will be required within the initial wellfield area and it is deemed appropriate to assume replacement of up to 10 wells each year for cost estimating purposes.

In order to maintain brine quality in the long term it may prove necessary to extend the initial wellfield on the basis of monitoring results over the early years of operation. For estimating purposes it is considered prudent to assume a progressive 50 percent extension to the wellfield area, with new wells sited on a 2 km grid, over the period 5 to 10 years after commencement of full scale production.

Recommendations concerning well design and the selection of pumping equipment are given to form a basis for capital cost estimates and maintenane requirements are assessed.

The importance of continuous monitoring of wellfield performance is stressed and it is recommended that a resource management model should be established, providing predictions of long term performance at six monthly intervals to facilitate planning of an ongoing exploration and well replacement programme.

The hydraulic complexity of the brine resource is such that performance predictions at this stage must be based on idealised modelling,assuming regional parameters derived from localised exploratory work on site and small scale laboratory tests. It is therefore necessary to adopt a flexible approach to development of the wellfield in the long term based on monitoring of performance of the initial production wells and taking full account of local variations in conditions.

Nevertheless, it is concluded that, with careful attention to wellfield management based on the recommended monitoring procedures, the resource as defined in Memorandum No.14 will sustain a yield of 18 x 10^6 m^3 per annum of brine at specific gravities in excess of 1.10 for more than 25 years.

APPENDIX A

Draft Performance Specification for Drilling and Well Construction Equipment

wlpu CONSULTANTS

SUA SODA ASH PROJECT

BRINE WELLFIELD

Draft Performance Specification for Drilling and Well Construction Equipment

CONTENTS

November 1984

1. PREAMBLE

The specification which follows is based on experience gained at Sua Pan during wellfield investigation drilling carried out over the period 1982-84.

The recommendations given regarding equipment types are provided for guidance only and tenderers will be free to propose alternatives based on their own assessment of site conditions, with due regard to the experience gained by others to date.

2. SITE LOCATION

The site comprises an area of some 1 000 km^2 of the Sua Pan, which forms part of the Great Makgadikgadi Depression in Northern Botswana.

The drilling operations will be based on the Sua Spit at Latitude 20^0 30' S Longitude 25^0 30' E. The elevation above sea level is approximately 900m.

The nearest major population centre is Francistown from which the site is accessible via some 180 km of tarred road.

An airstrip is available at site, suitable for light aircraft.

3. CLIMATE

The rainy season typically extends from November to April and annual average rainfall is approximately 400mm.

The rainfall is erratic both in areal extent and intensity.

Average ambient temperatures during the rainy season are in the range 18^0 to 32^0 C and during the dry season in the range 5^0 to 23^0 C. Frost may occur during the dry season, particularly in June and July. Although the rainfall is generally concentrated over the period November to April, local intensive rain showers may occur during the remaining "dry season" months.

The environment is dusty other than during rainy periods and intense dust storms are experienced on the Pan during which visibility can be reduced virtually to zero.

4. THE BRINE WELLFIELD

The soils of the Sua Pan are underlain by concentrated brines typically of specific gravity about 1.12 and the brine table typically lies at 1 to 2m below the ground surface.

The objective of the brine wellfield is to supply brine at an average continuous rate of 660 l/s and a peak rate of 1 200 l/s to solar evaporation ponds.

In the solar ponds the brine is concentrated by evaporation to saturation in sodium chloride, then to saturation in sodium carbonate at which stage the concentrated liquor is fed to a process plant.

The plant will produce some 400 000 tonnes per annum of common salt ($NaCl$) and 300 000 tonnes per annum of sodium carbonate (Na_2CO_3).

The brine is corrosive to metals subject to oxidation and is particularly corrosive to unprotected mild steel in the presence of oxygen.

Typical analyses of the brine from existing wells are tabulated below for guidance purposes with salt concentrations expressed in g/l:

SG	$NaCl$	Na_2CO_3	$NaHCO_3$	Na_2SO_4	KCl	pH
1,125	138,0	19,6	12,4	14,6	3,7	9,0
1,122	113,1	27,4	6,9	12,6	4,6	9,4
1,125	132,9	22,1	9,6	14,0	4,6	-

Abundant bacteria and H_2S gas are also present in the natural brine.

It is envisaged that the initial wellfield will comprise some 60 wells with an average yield of about 20 l/s of brine. Standby wells will be provided to be brought into production in the event of failure or depletion of the initial production wells and there will be an ongoing requirement to put down replacement wells over a period of some 25 years.

5. VEHICLE REQUIREMENTS

The surface soils of the Sua Pan exhibit low bearing capacities of the order of 25 kN/m^2. During the wet season rainfall ponds on the surface of the Pan causing extensive but short term flooding, often to a depth of 100mm. This flooding results in a further lowering of bearing capacity and considerable loss of vehicle traction.

The drilling rig, pump installation unit, ancillary equipment transporters and support vehicles will necessarily be of the tracked or multi-wheeled, low ground bearing pressure type. Stability against differential settlement will be obtained by utilising a low profile type vehicle having a low centre of gravity.

Vehicles of the wide flexible tracked variety are favoured, offering substantially reduced bearing pressures and maximum traction. It is envisaged that vehicles will have dented tracks having a heavy duty rubber covered nylon cord belting, or similar, with an overall track width in the region of 1m each.

Alternatively, the required combination of low ground bearing pressures and traction could be obtained by utilising low pressure tyres set in clusters on multiple axles to evenly distribute the load. Such a vehicle would require drive transmitted to all wheels.

Due to the remoteness of the area and adverse environmental conditions including wind-blown dust and the corrosive properties of the Sua brine, simplicity of design, ruggedness and ease of maintenance and repair will be essential for all vehicles.

It is envisaged that the drilling rig would be powered by a sturdy and reliable diesel engine of simple design. The vehicle would be comprised solely of a track or wheel mounted unit supporting the engine, hydraulic system and drilling derrick. A power take-off from the truck engine would be available to operate the drill and derrick. Hydraulic levelling jacks will also be required at the front and rear. A maximum speed of some 12 km/hr will be sufficient.

A diesel engined air compressor and high pressure brine circulating pump fitted to a wheel mounted support unit may be towed behind the drilling rig. Other support vehicles with trailers will be required for the brine supply pump and for delivery of drilling rods, casings, well screens, fuel and the like to drilling sites up to 30km from the base facilities and for the installation of pumps.

6. BRINE WELL CONSTRUCTION

The brine wells will be of 375mm nominal diameter incorporating well screens and casing of 250mm nominal diameter.

The holes will be drilled generally through soft, unconsolidated formations comprising sands, silts and clays with occasional thin bands of hard chalcedony, calcretes and silcretes occurring at various depths. In some locations the formations are cemented to form hard and continuous sandstones and siltstones and the rig shall be capable of penetrating these formations as and when required.

The screens and casings will be of PVC with a net dry weight of up to 20 kg/m.

The annulus between the screen and the hole wall will be packed with a graded filter medium. The design grading of this material is shown on Fig.1.

Wells will typically be of 30 to 40m depth, but the rig shall be equipped to drill to 100m depth if and when required.

The rig and support vehicles shall be capable of carrying sufficient rods, casing, screens, fuels and consumables to construct 2 wells up to 100m in depth and up to 30 km from the base facilities without returning to base.

7. DRILLING EQUIPMENT

The rig shall be of the tophead drive, rotary hydraulic type with automatic feed and adjustable down pressure to provide maximum penetration rate in varying formations. A winch line shall be available suitable for the installation of well screens. The air compressor and high pressure circulating pump shall be of capacities suitable for operation in wells of the dimensions specified above. The low pressure brine supply pump shall provide high resistance to abrasion.

To minimise disturbance and risk of collapse of the hole during drilling, the reverse circulation system shall be employed. A rotary cutter head,drag type bit or similar shall be utilised. A temporary steel casing to provide an internal hydrostatic head to control collapse during drilling, screen installation and sand packing shall be supplied at the top of the hole. The large volumes of fluid required for reverse circulation drilling are readily available from the brines occurring typically 1 to 2m below the surface of the Pan.

The velocity of drilling fluid down the hole must be low enough to avoid erosion of the hole walls and the drilling techniques shall be such that the tendency for fines to be forced laterally into the aquifer is minimised.

8. DRILLING FLUID

Both the natural brines and revertible organic polymer type muds have been used during exploratory drilling on the Pan.

Experience has suggested that in the proposed wellfield area the natural brines may be used exclusively provided that a positive head is maintained in the hole when the drill string is withdrawn and that the screens and sand pack are installed without delay under a sustained outward hydraulic gradient.

Tenderers are to allow for pumping of the required flow of drilling brine continuously from sumps provided in advance by the Client within 50m of each well site.

9. REPRESENTATIVE DISTURBED SAMPLING

Continuous sampling will be required to allow easy examination and appraisal of the horizons being drilled. The high velocities up the inside of the drill pipe will reduce separation of the cuttings to a minimum, assisting logging and strata identification. Suitable sample catchers shall be provided to obtain representative samples carried in large volumes of high velocity return drilling brine.

10. INSTALLATION OF WELL SCREENS

On completion of drilling the well, screens must be installed. Screens and casings will be supplied in standard lengths of up to 6m. The wells will be drilled largely in unconsolidated materials, prone to collapse, and methods of screen installation shall take this into account. Prior to installation the screens will be fitted with centralising guides giving an effective overall diameter of 375mm.

11. INSTALLATION OF GRAVEL PACK

Gravel pack shall be placed in the annular space between the well screen and the sides of the hole in a manner that avoids segregation or particles "hanging up" leaving voids in the annulus.

It is envisaged that the gravel pack will be placed either by pumping or gravity feeding in a brine slurry through a tremmie system.

12. WELL DEVELOPMENT

In order to obtain maximum production efficiency from the brine wells they shall be developed before use. Development can be achieved by surging with compressed air blown through a jetting tool, similar to airlift pumping. This shall be carried out until the brine is clear and free of fines. The volume and pressure capacity of the air compressor shall be such that adequate development in a well of 375mm diameter and maximum depth of up to 100m can be achieved.

13. PUMP INSTALLATION

The tenderer shall supply a pump installation unit based on a similar low ground bearing pressure chassis to that employed for the drilling rig.

The pumps will be top drive Mono BH400 units set at depths of up to 30m.

The pump installation unit shall incorporate a lifting derrick and winch capable of handling the top drive unit, up to 30m of riser column plus the rotor/stator and intake unit. The safe working load of the derrick shall be 1.5 *tonne (minimum)*.

The pump installation unit shall be capable of carrying two pumps, each with a 30m riser column, to sites located up to 30 km from base facilities and shall carry sufficient fuel and consumables to carry out two installations without returning to base.

14. ANCILLARY EQUIPMENT

The tenderer shall supply suitable ancillary equipment and tools (e.g. support vehicles, brine supply pump, circulatory pump, air compressor, drilling rods adequate for a 100m drill string, fishing tools and lighting for night operation) to enable holes of the prescribed dimensions and depths to be drilled, screened, gravel packed, developed, equipped and production tested.

It is envisaged that the following minimum inventory of major plant items will be required:

i) 1 No. fully equipped drilling rig
ii) 1 No. diesel powered low pressure brine supply pump
iii) 1 No. diesel powered high pressure brine circulating pump
iv) 1 No. diesel powered air compressor
v) 1 No. heavy duty towable support vehicle
vi) 1 No. heavy duty self-propelled support vehicle
vii) 3 No. light towable trailers, i.e. one large, two small
viii) 1 No. fully equipped pump installation unit.

15. PRODUCTION TESTING EQUIPMENT

The Client will supply flow meters, pumping equipment and dippers for acceptance testing at each well site.

16. SPARES

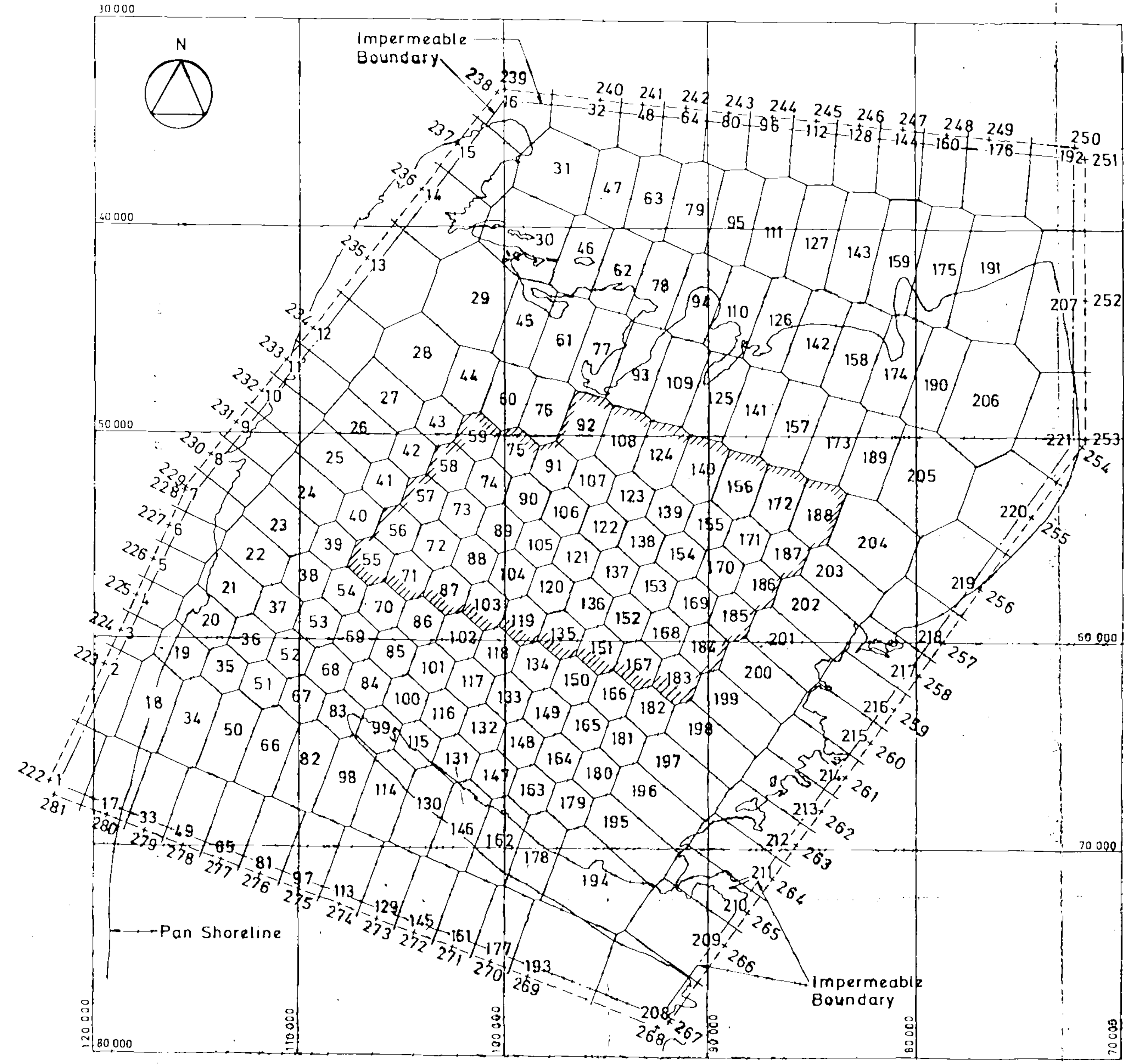
The tenderer is to offer a complete set of spares adequate for maintenance of all equipment covered by this specification in a reliable operating condition for up to 1 year during which period up to 70 production wells will be constructed.

The tenderer shall list the spares included in his bid.

17. FUEL AND LUBRICANTS

The tenderer shall indicate in his bid the fuel and lubricant consumptions of the equipment offered both per hole drilled to 35m depth and per kilometre travelled fully laden between set ups.

FIG. 1



0 5 Km

NOTES

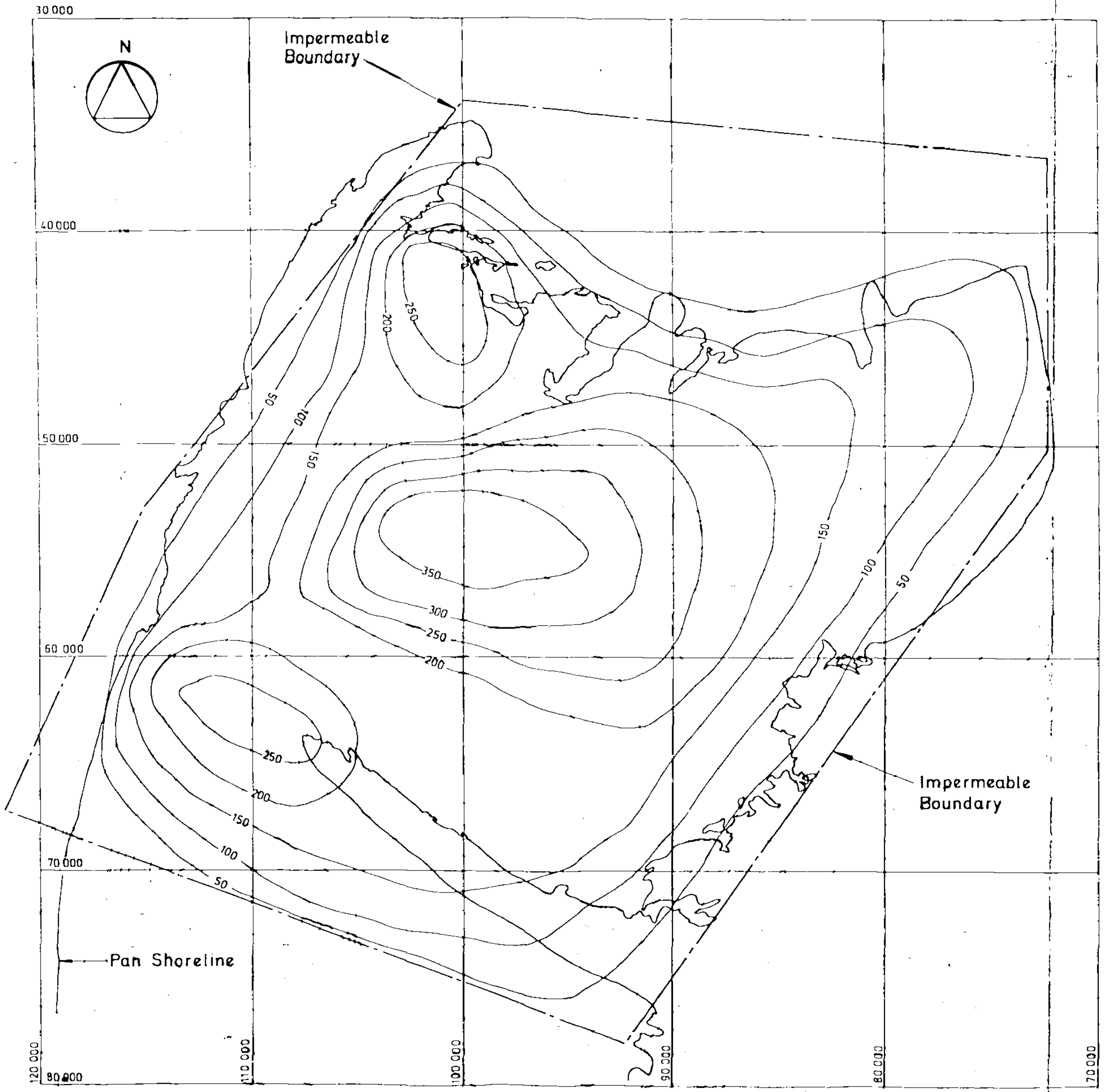
Internal Nodes 1-221

External Nodes 222-281 (Used purely to define Boundaries)

Perimeter of Wellfield

FINITE DIFFERENCE MESH

FIG. 2

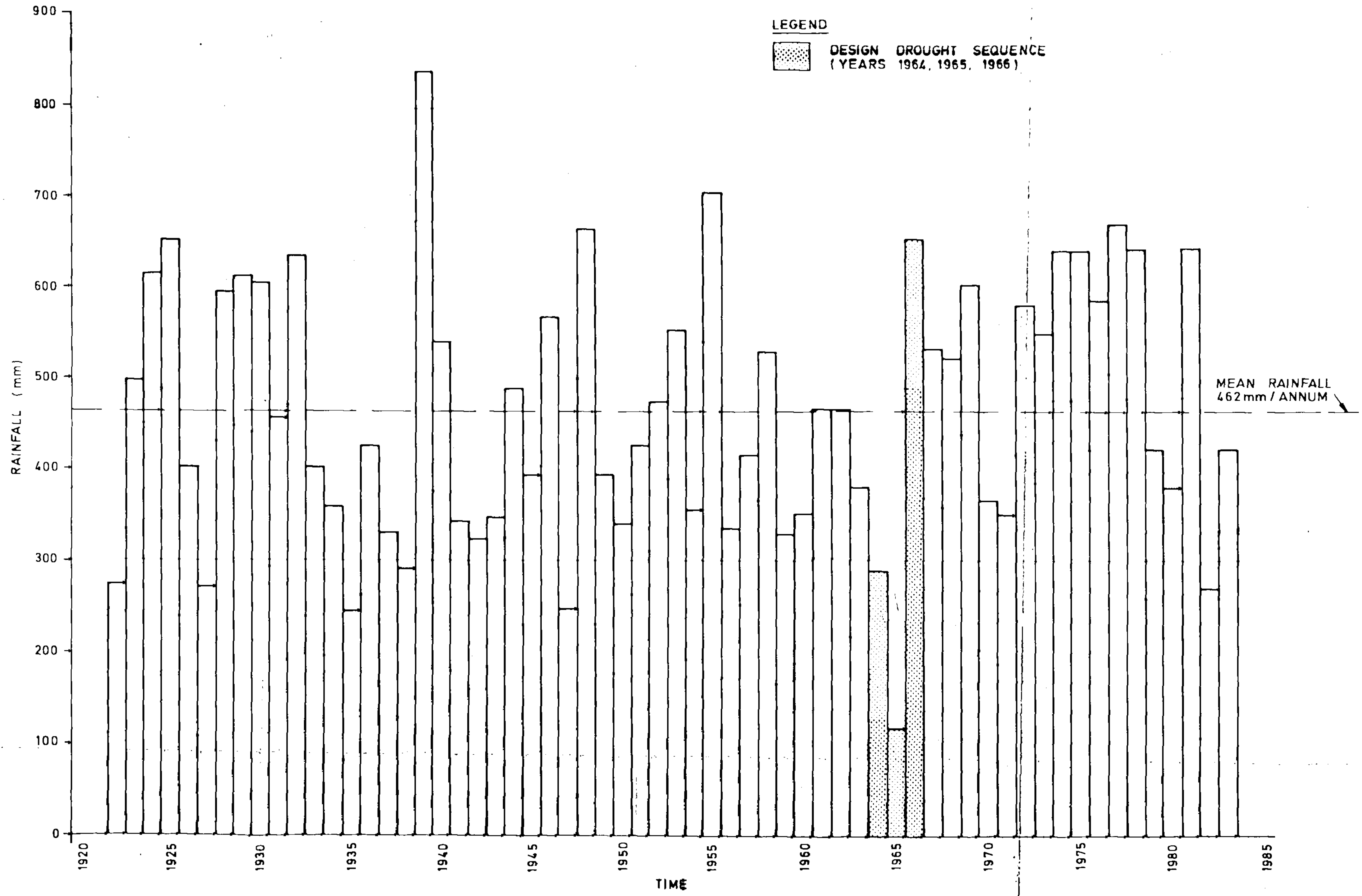


NOTES:

1. IMPERMEABLE BOUNDARY ASSUMED TO BE A CONTOUR OF ZERO TRANSMISSIVITY.
2. TRANSMISSIVITIES GIVEN IN m^2/ DAY

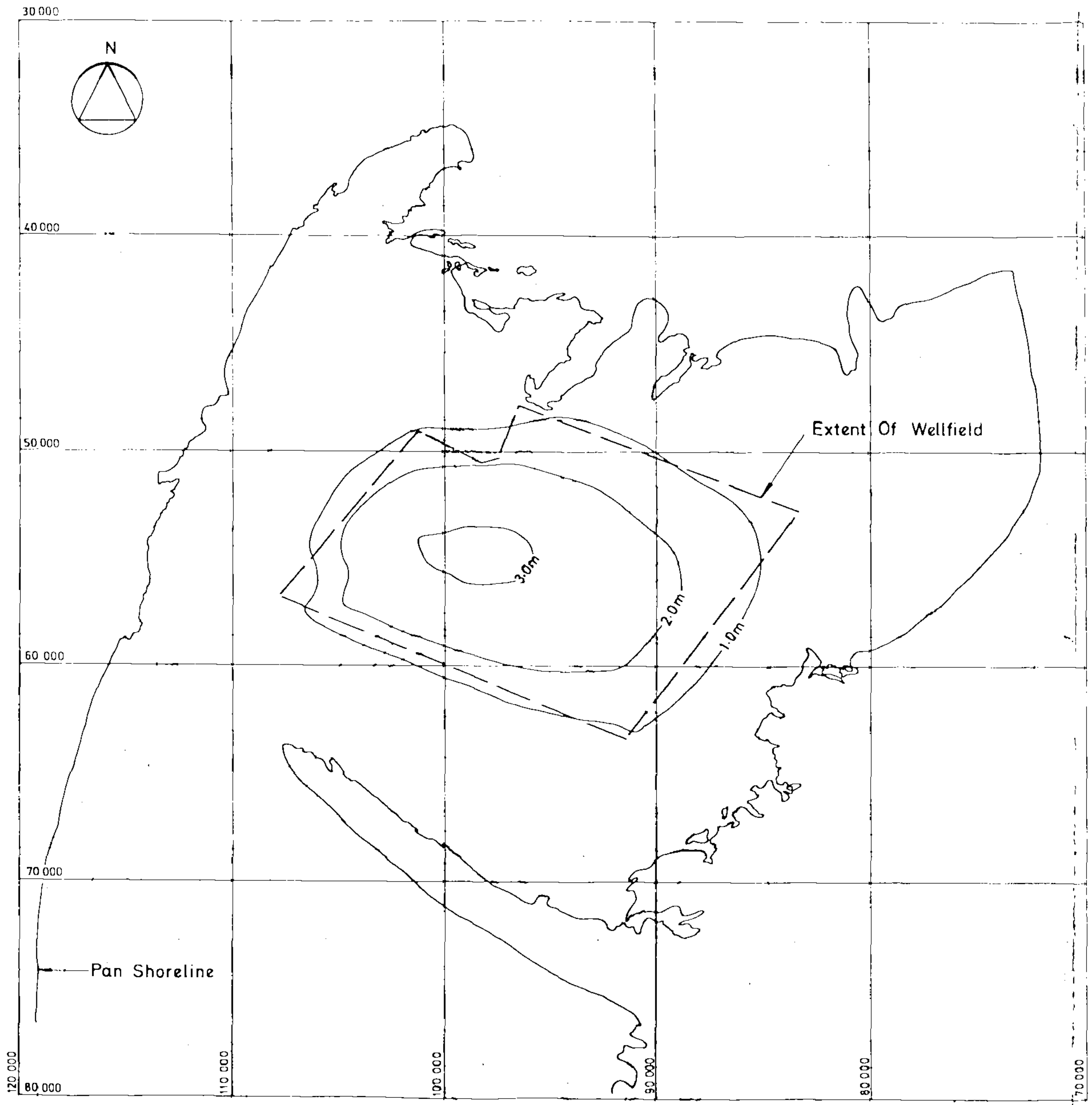
INTERPOLATED TRANSMISSIVITY CONTOURS USED IN COMPUTER MODEL

FIG. 3



FRANCISTOWN RAINFALL RECORDS (1922 - 1983)

FIG. 4

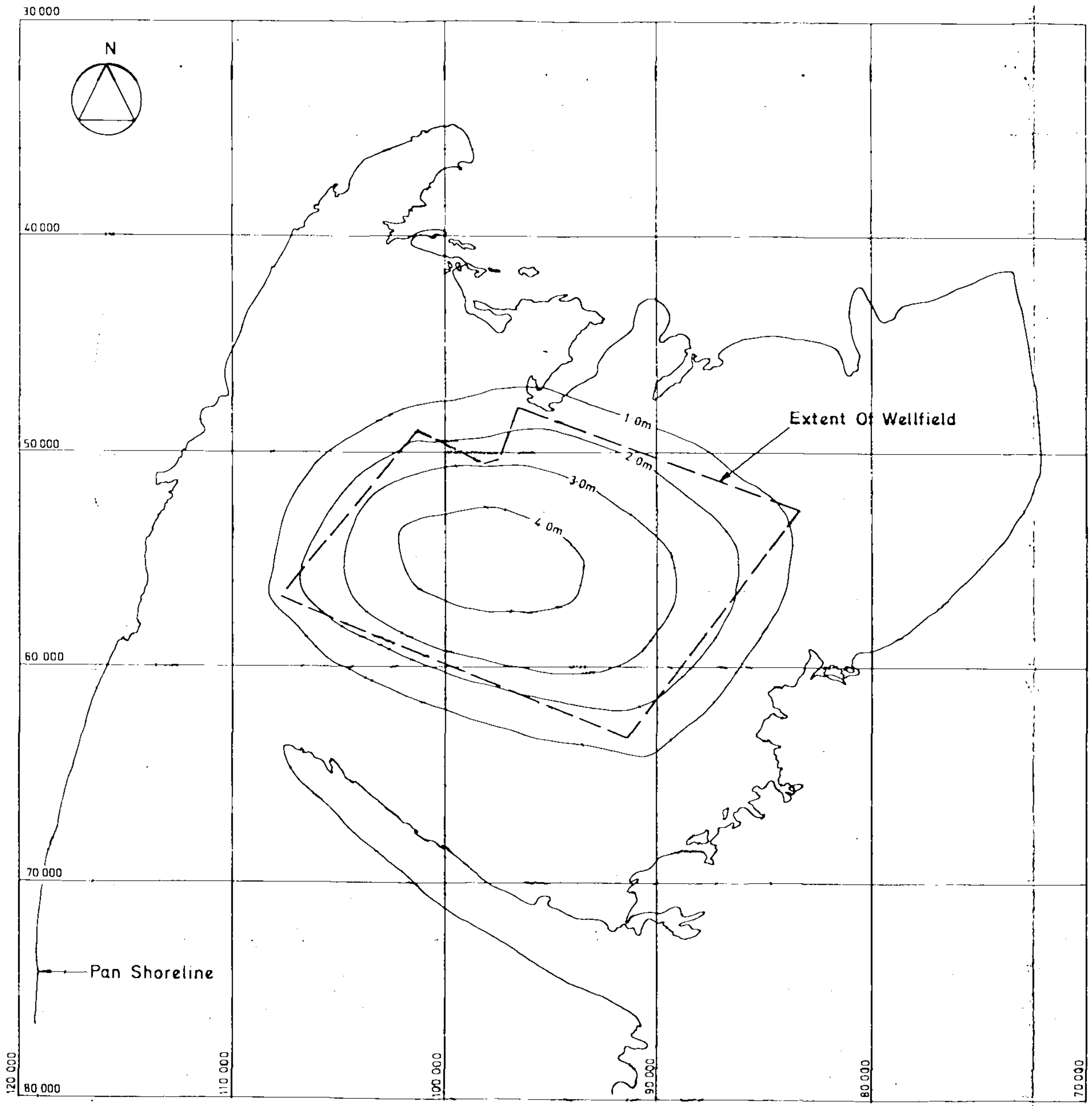


NOTES

1. ALL DRAWDOWNS ARE GIVEN AT 650m FROM WELLS.
2. CONTOURS ARE FOR SITUATION AT THE END OF MONTH 32 IN THE 3 YEAR SIMULATION PERIOD
3. MAXIMUM DRAWDOWN AT THE CENTRE OF THE WELLFIELD IS 3.144 m.

DROUGHT SIMULATION - DRAWDOWN CONTOURS FOR 10 m. AQUITARD

FIG. 5



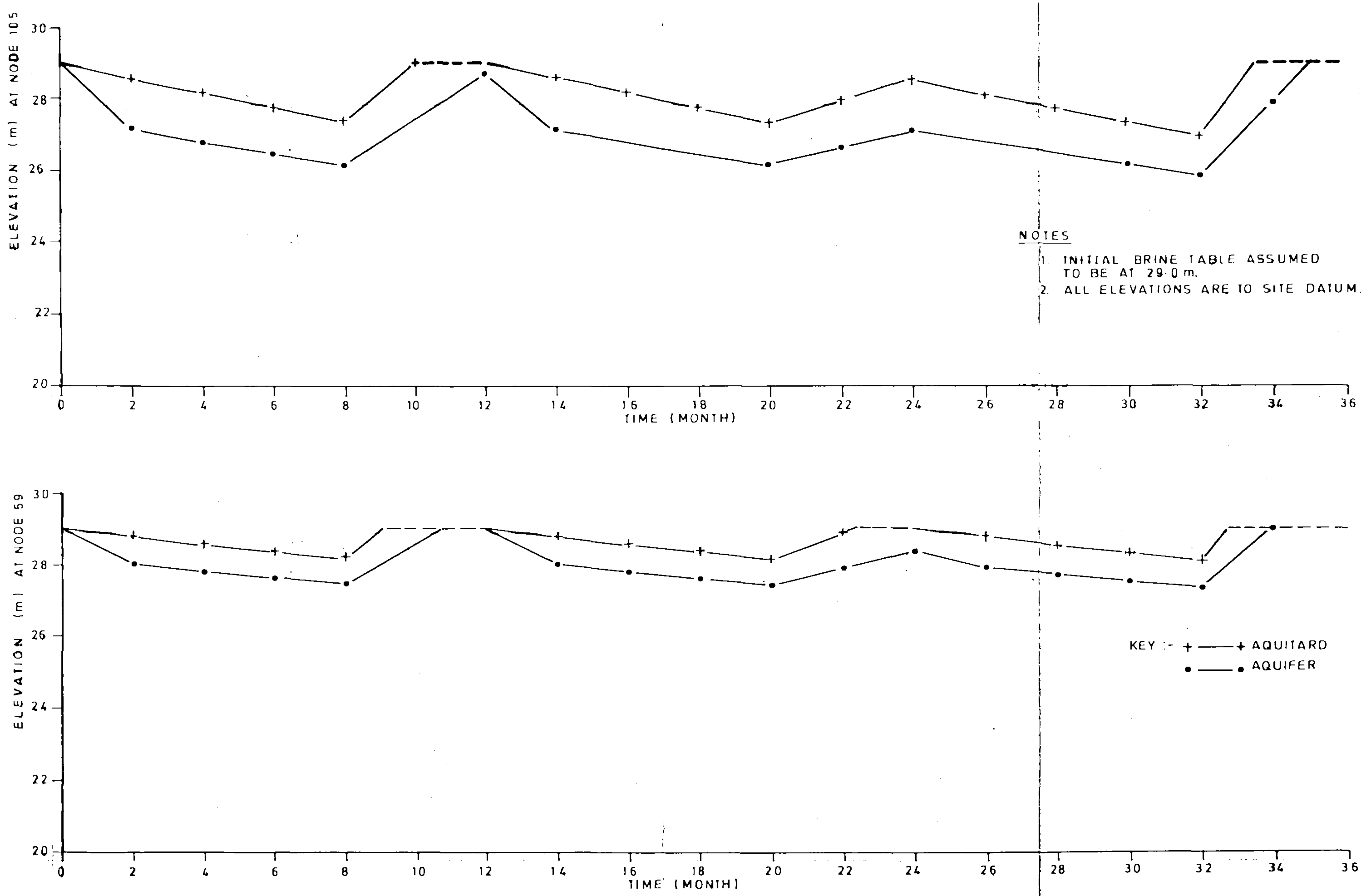
0 5 Km

NOTES

1. ALL DRAWDOWNS ARE GIVEN AT 650m FROM WELLS.
2. CONTOURS ARE FOR SITUATION AT END OF MONTH 32 IN THE 3 YEAR SIMULATION PERIOD.
3. **MAXIMUM DRAWDOWN AT THE CENTRE** OF THE WELLFIELD IS 4·441m.

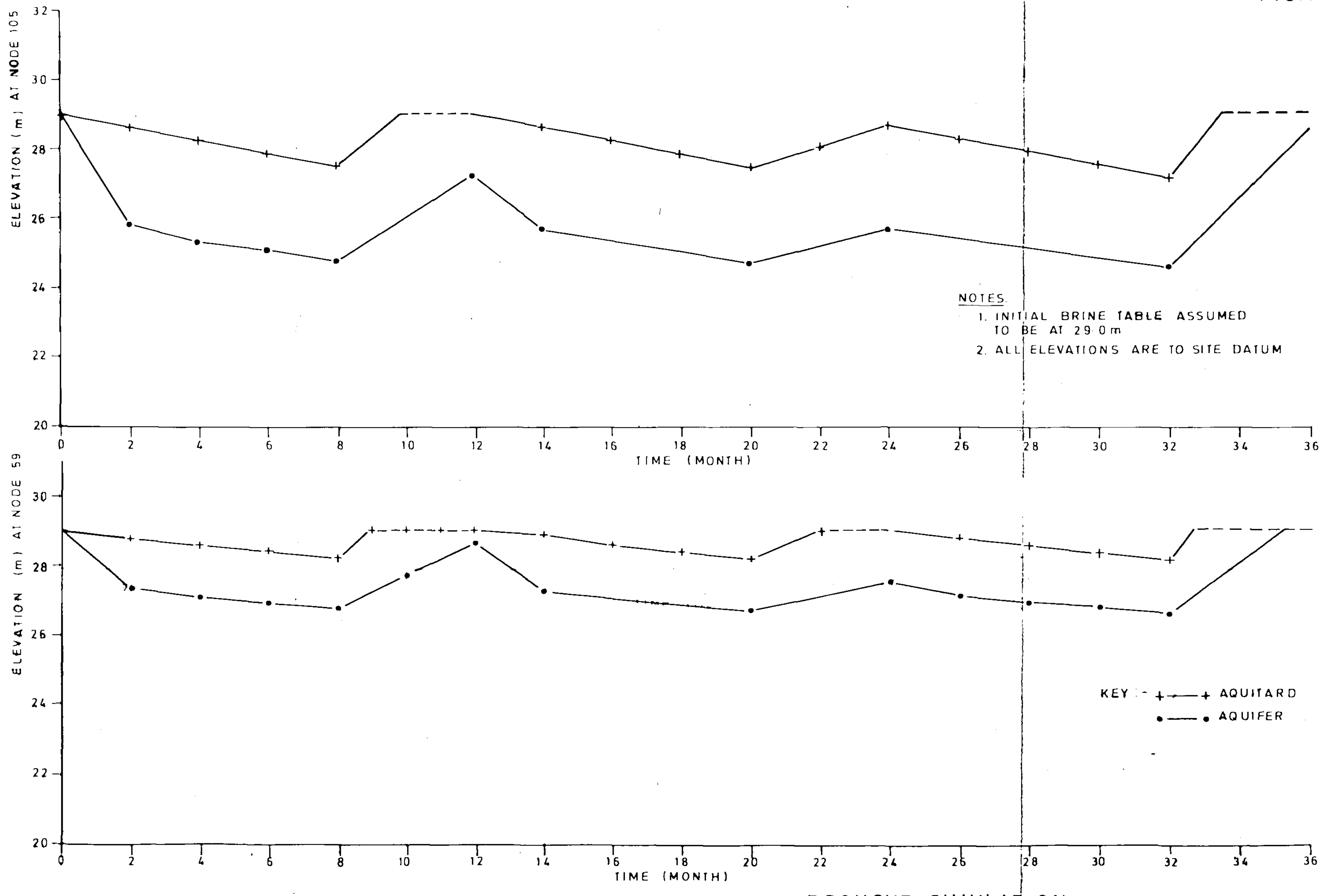
DROUGHT
SIMULATION - DRAWDOWN
CONTOURS FOR 20m AQUITARD

FIG .6



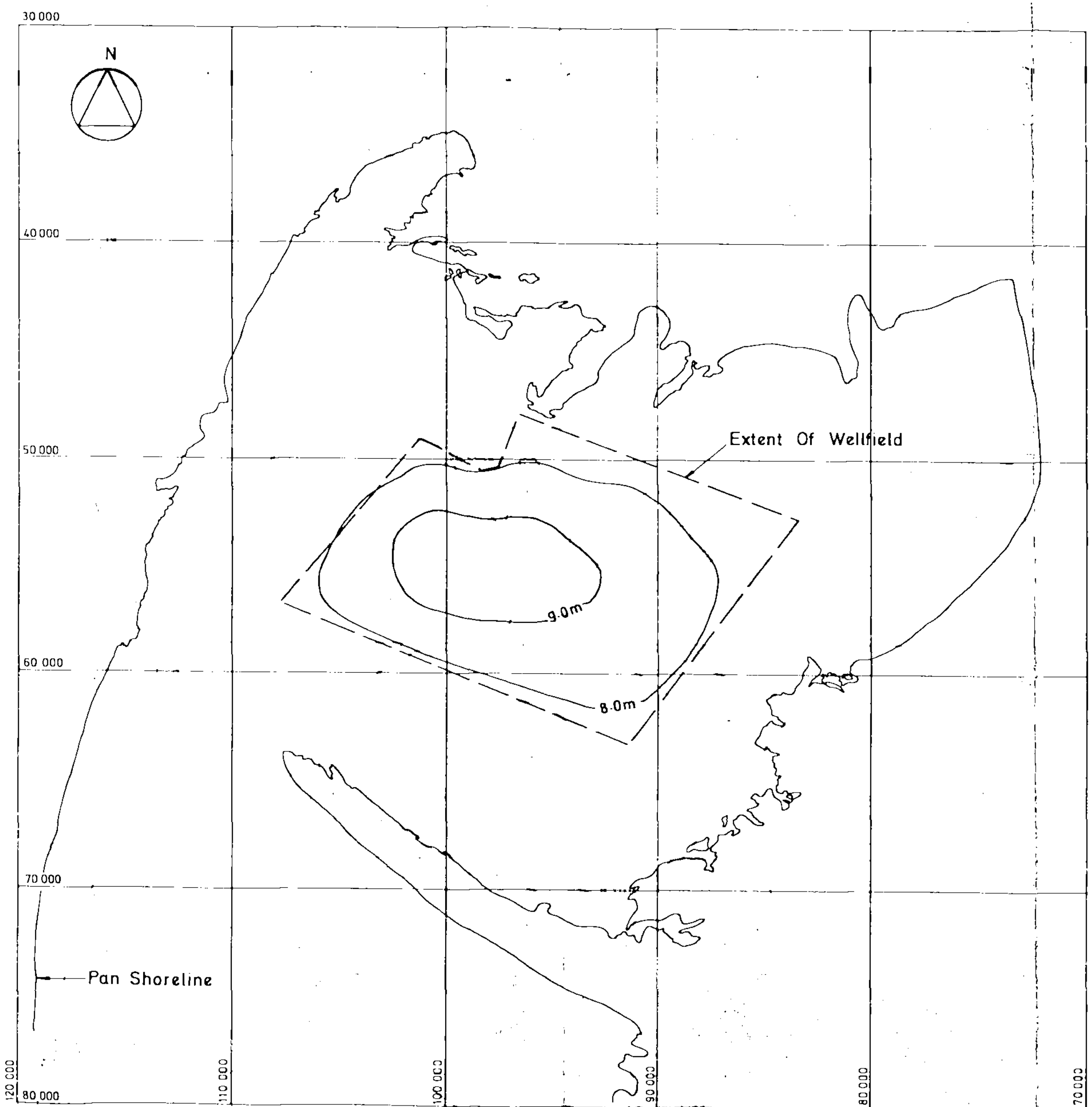
DROUGHT SIMULATION -
DRAWDOWN VERSUS TIME FOR 10m AQUITARD

FIG.7



DROUGHT SIMULATION -
DRAWDOWN VERSUS TIME FOR 20m AQUITARD

FIG. 8



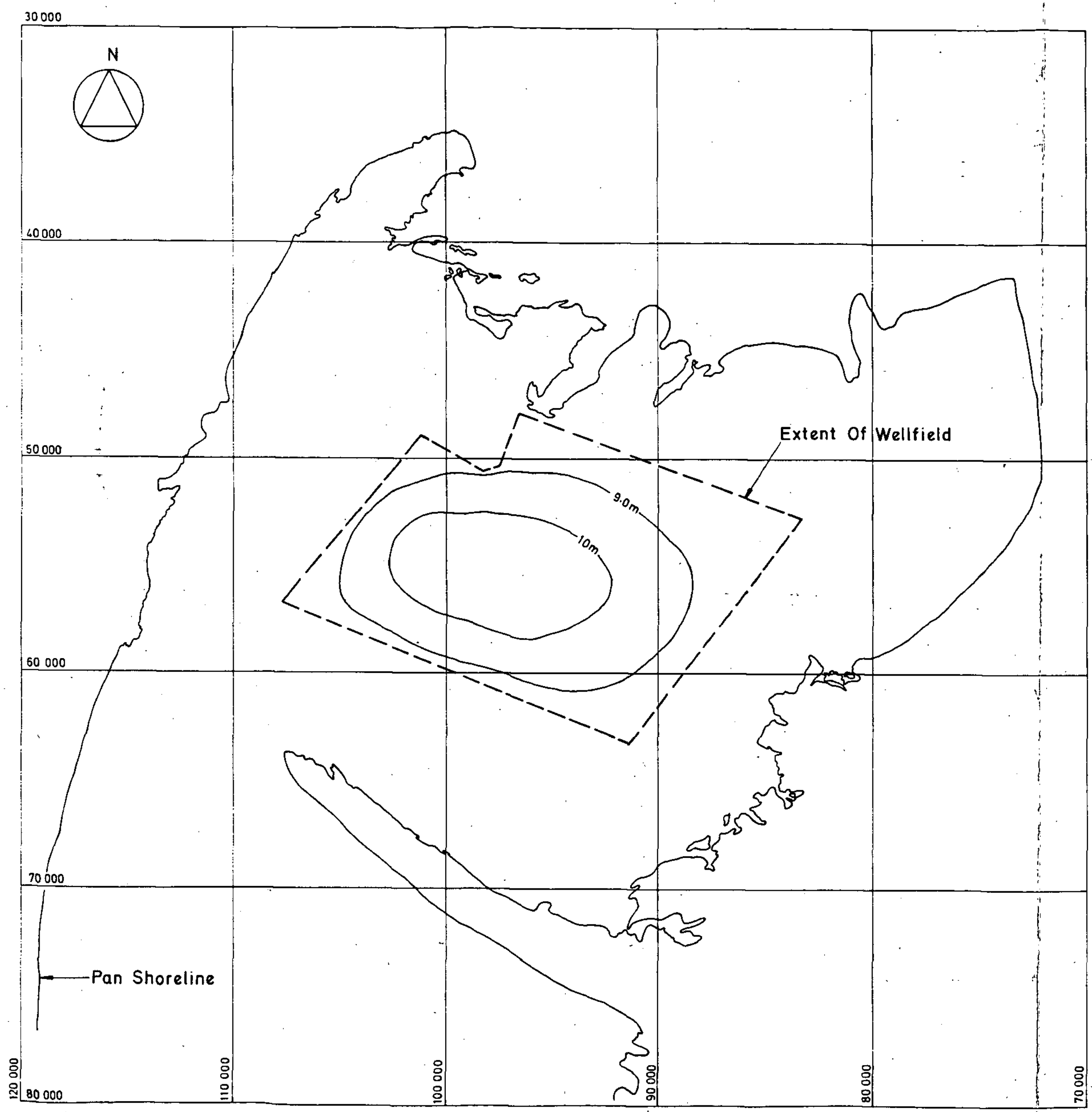
0 5 Km

NOTES

1. ALL DRAWDOWNS ARE GIVEN AT THE WELLS
2. MAXIMUM WELL DRAWDOWN AT THE CENTRE OF THE **WELLFIELD** IS 9.32 m.
3. CONTOURS SHOW CONDITIONS AFTER 8 MONTHS CONTINUOUS PUMPING AT 660 l/s WITH ZERO RECHARGE.
4. PLOTTED DRAWDOWNS ARE EXCLUSIVE OF WELL LOSSES.

AVERAGE RECHARGE SIMULATION - WELL DRAWDOWN CONTOURS FOR 10m. AQUITARD

FIG.9



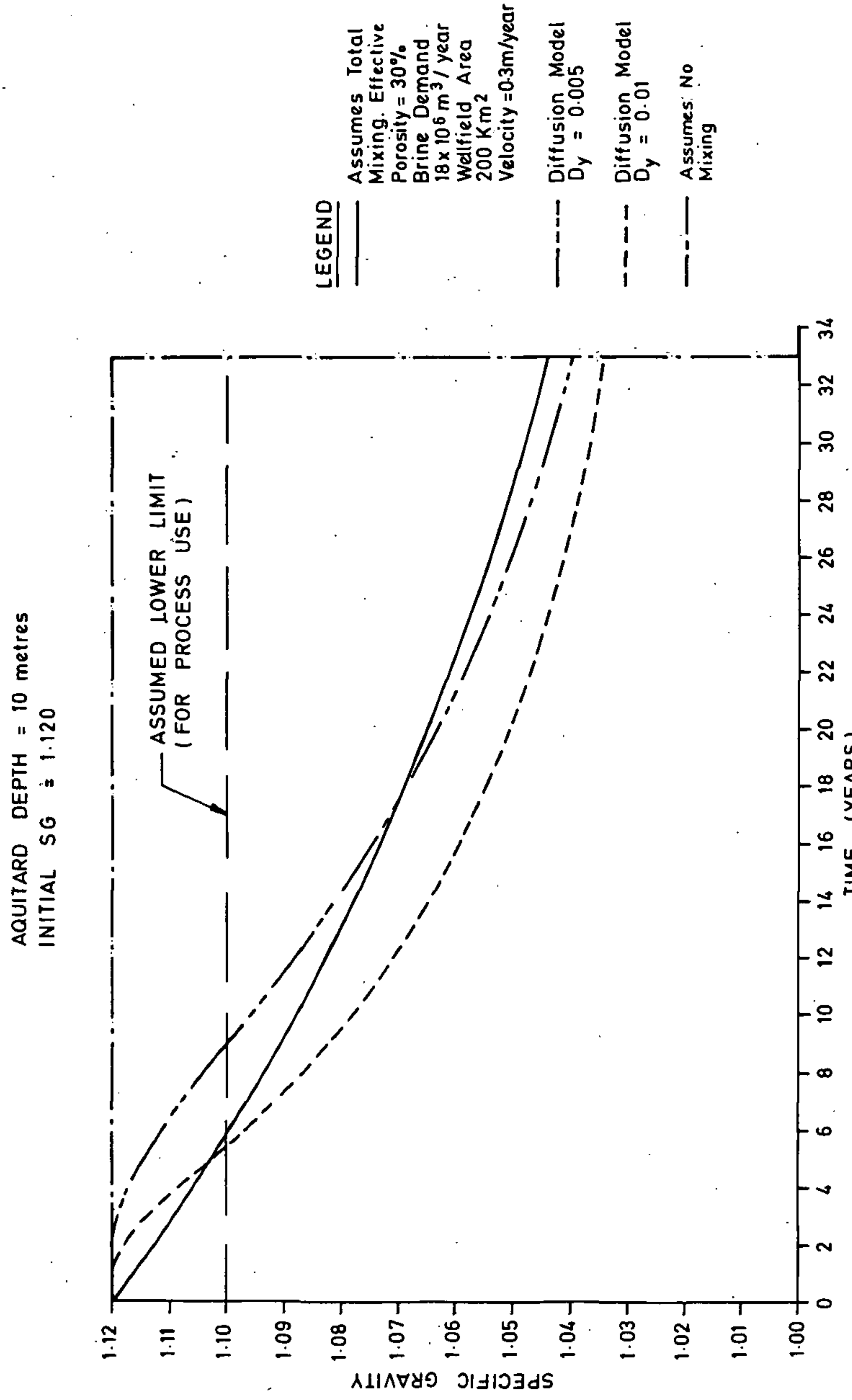
0 5 Km

NOTES

1. ALL DRAWDOWNS ARE GIVEN AT WELLS.
2. MAXIMUM WELL DRAWDOWN AT THE CENTRE OF WELLFIELD IS 10.53m.
3. CONTOURS SHOW CONDITIONS AFTER 8 MONTHS CONTINUOUS PUMPING AT 660 l/s WITH ZERO RECHARGE.
4. PLOTTED DRAWDOWNS ARE EXCLUSIVE OF WELL LOSSES.

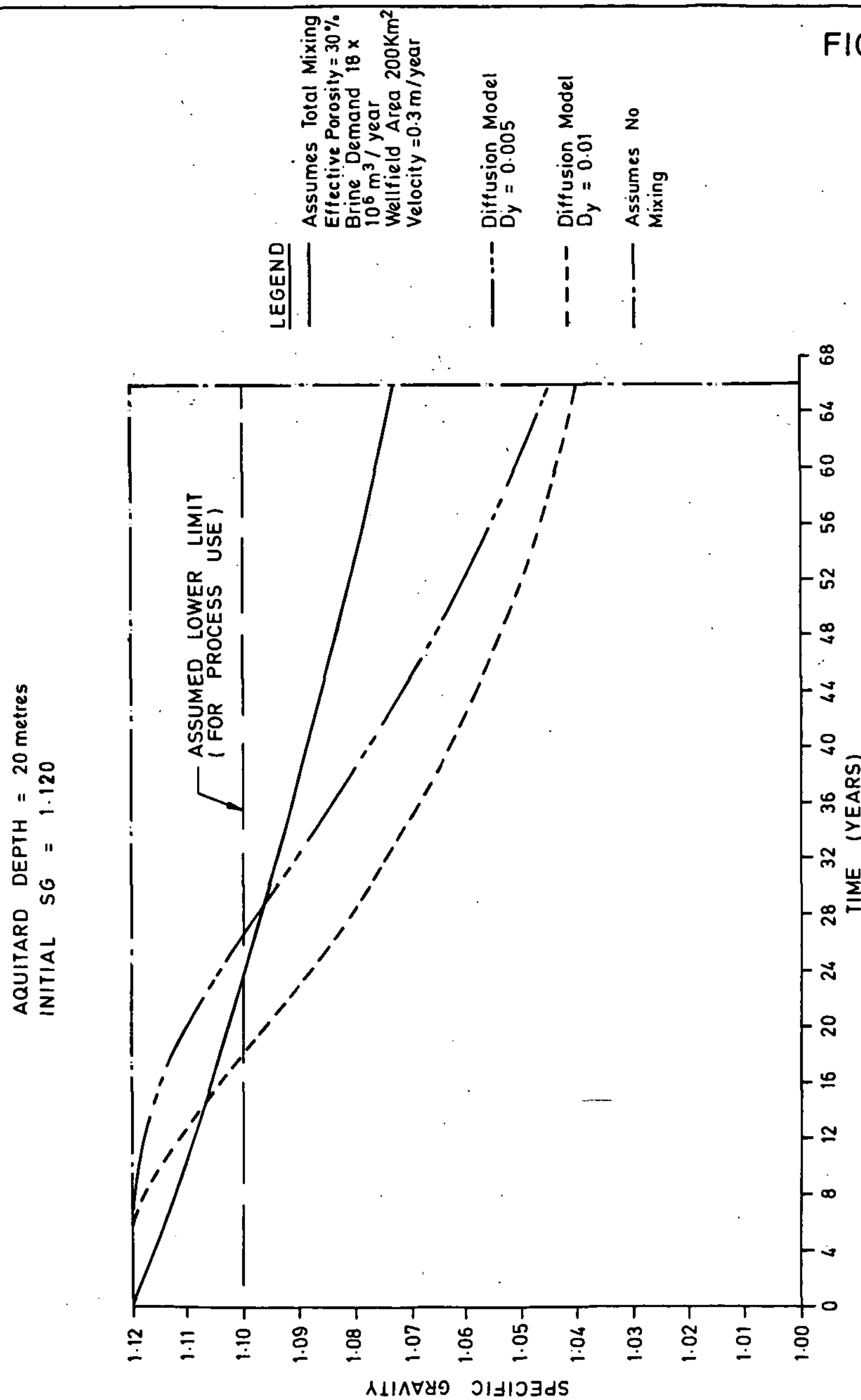
AVERAGE RECHARGE SIMULATION - WELL DRAWDOWN CONTOURS FOR 20m AQUITARD

FIG.10



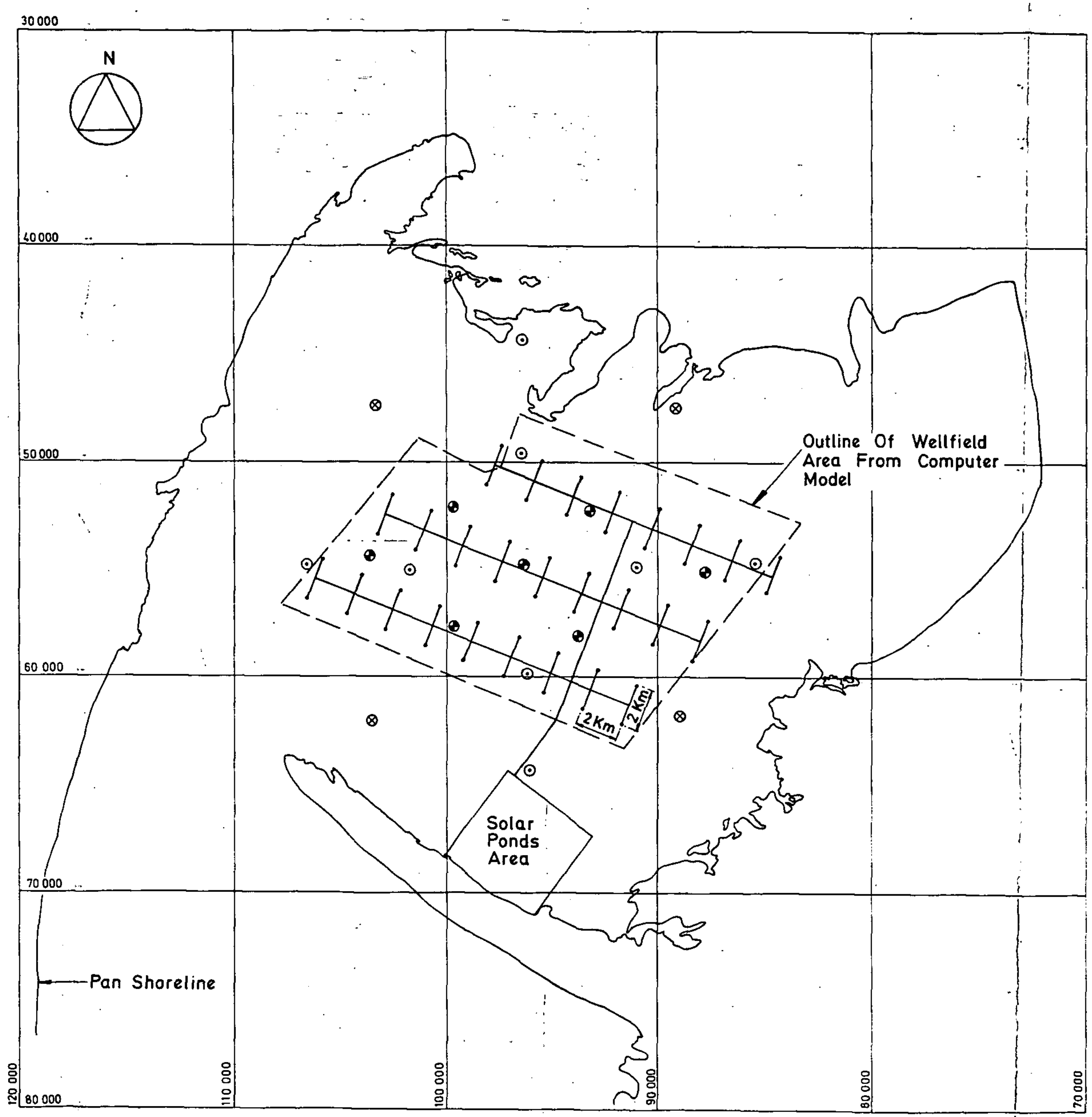
DECLINE IN BRINE S.G.
WITH TIME FOR 10m AQUITARD

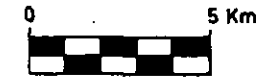
FIG. 11



DECLINE IN BRINE S.G.
WITH TIME FOR 20m AQUITARD

FIG. 12





NOTES

1. DISTRIBUTION PIPEWORK LAYOUT NOTIONAL AND SUBJECT TO OPTIMISATION

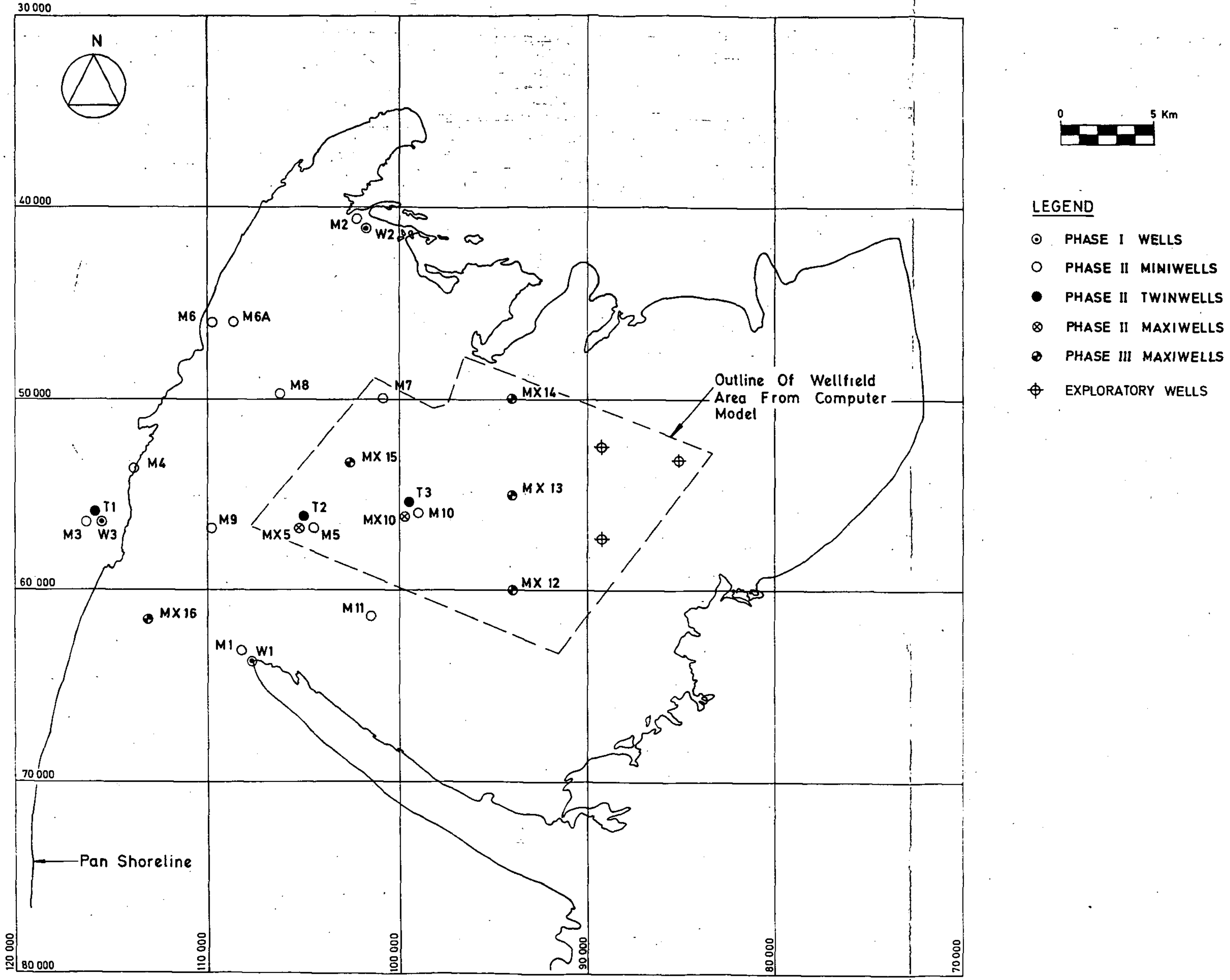
2. AUGER HOLES FOR AQUITARD MONITORING TO BE SUNK ADJACENT TO WELLS TYPE 'A' AND 'B'

LEGEND

- TYPE 'A' MONITORING WELL
- TYPE 'B' MONITORING WELL
- TYPE 'C' MONITORING WELL
- PRODUCTION WELL

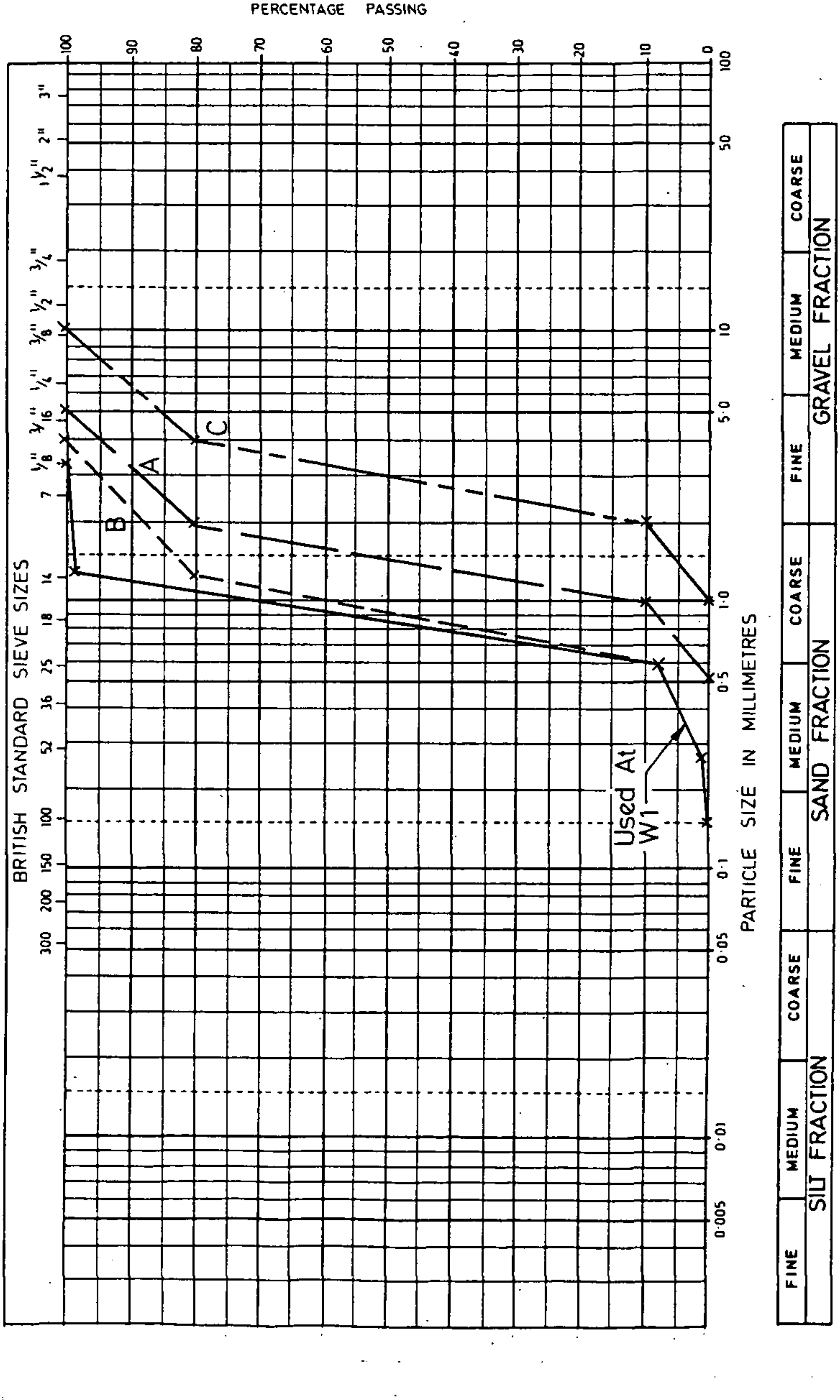
INITIAL WELLFIELD AND MONITORING SYSTEM LAYOUT

FIG. 13



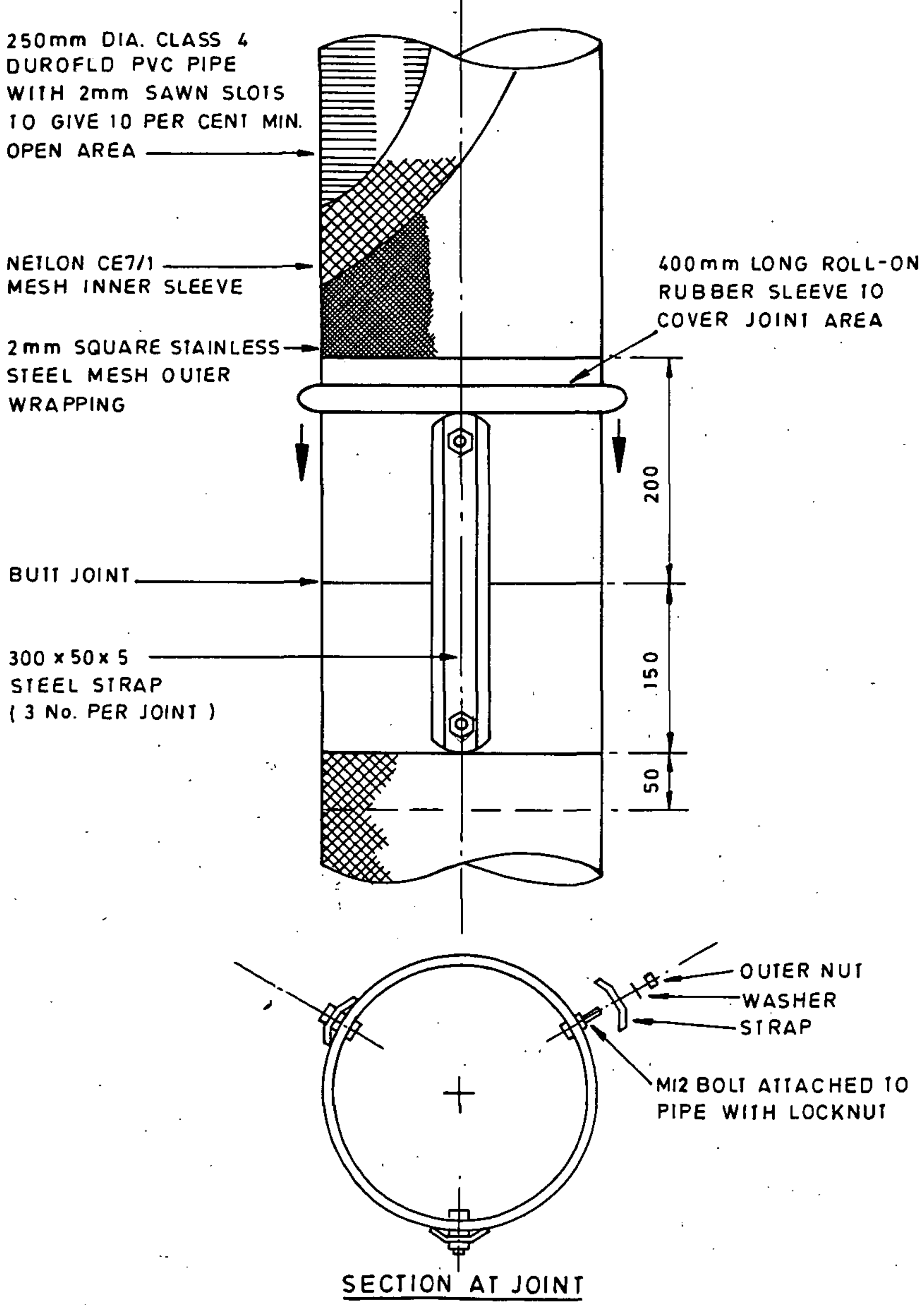
PROPOSED EXPLORATORY WELLS

FIG. 14



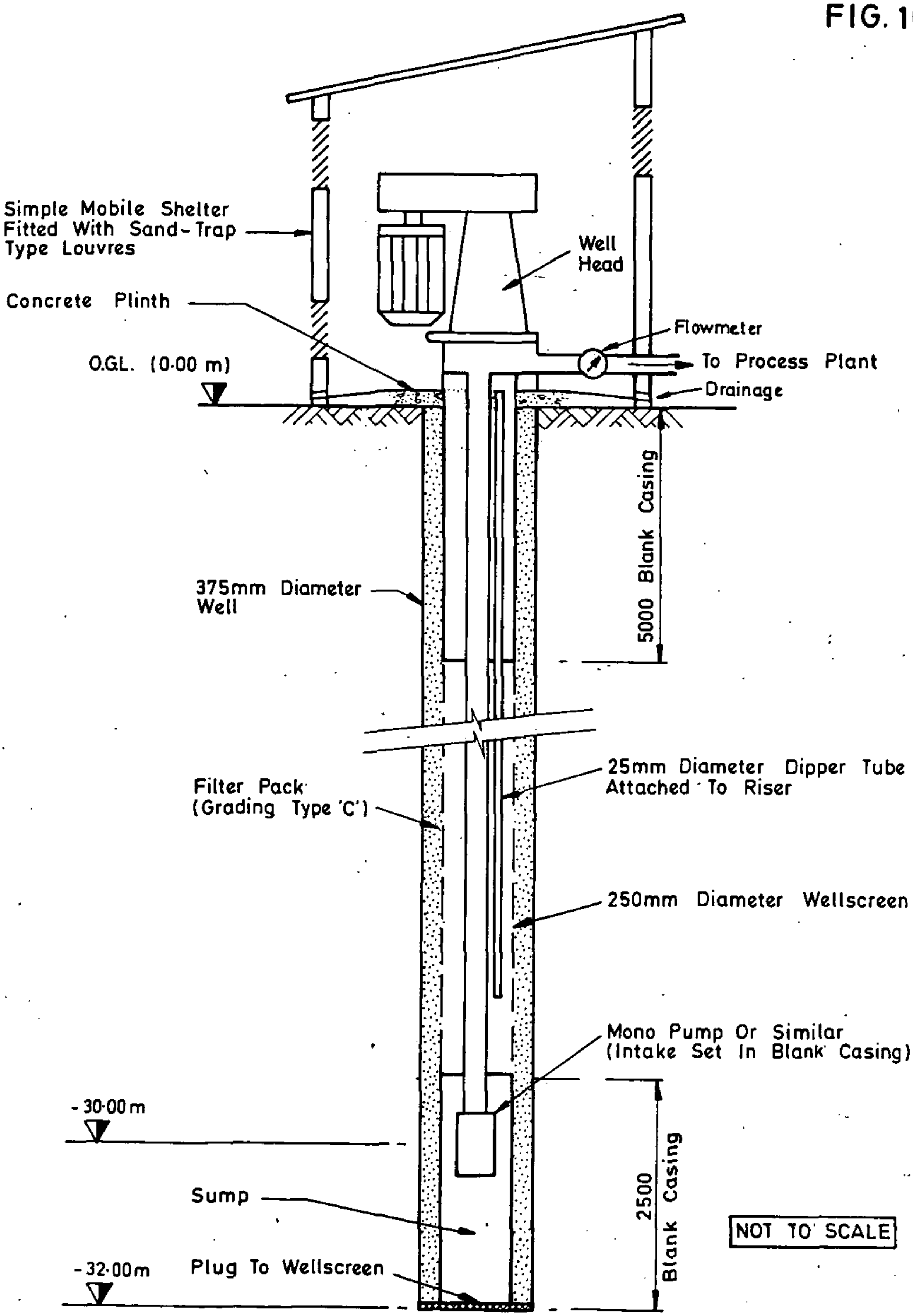
FILTER PACK GRADINGS

FIG. 15



WELL SCREEN DETAILS

FIG. 16

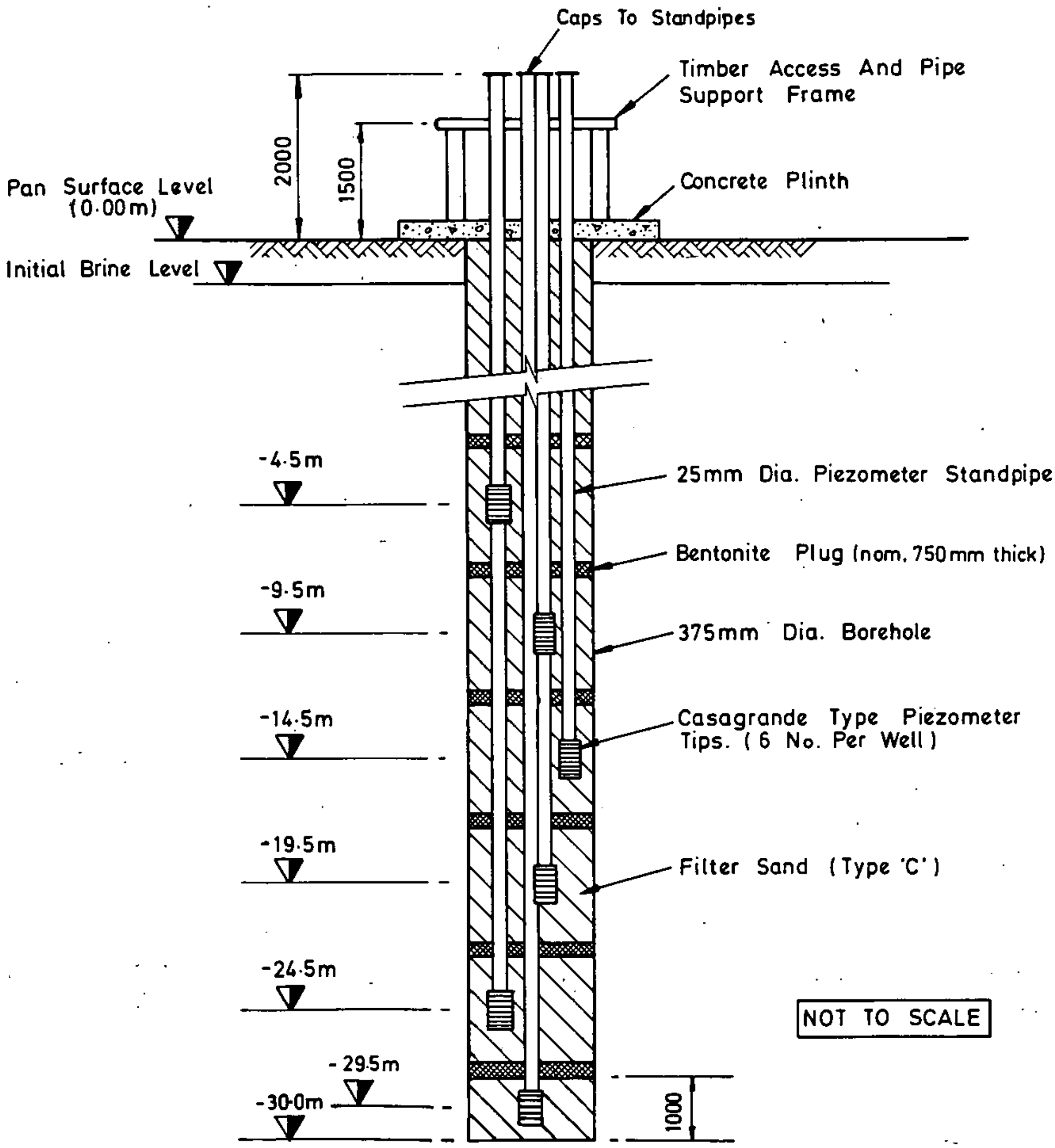


NOTES

1. See Figure 15 for wellscreen proposals.
2. Pump motor to be set above estimated maximum flood level
3. Shelter to be adequately ventilated for motor cooling

TYPICAL WELL DETAILS

FIG. 17



DETAILS OF BRINE QUALITY MONITORING WELL (TYPE 'C')